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INTEGRATED GRAVITY MAPPING SYSTEM (IGMS) STUDY PROGRAM  
FOR AIRCRAFT AND L. (U) BELL AEROSPACE TEXTRON BUFFALO  
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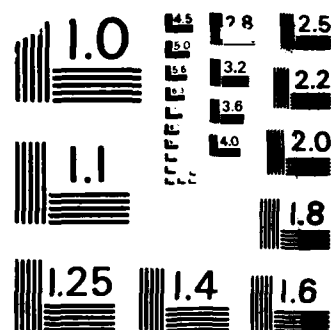
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Integrated Gravity Mapping System (IGMS) Study  
Program for Aircraft and Land Vehicles

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March 1982

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June 1981 - February 1982

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## FOREWORD

This is the outline of the complete IGMS Final Technical Report.

### Volume I - Final Technical Report without Appendices

- 1.0 Introduction
- 2.0 Summary
- 3.0 Description of GSS ADM System
- 4.0 Gravity Survey Performance Analysis
- 5.0 Mission Requirements
- 6.0 Design Modifications Requirements
- 7.0 Technical Description/Tradeoffs of the IGMS Configuration
- 8.0 Conclusions and Recommendations

### Volume II - Appendices

- A The Rotating Accelerometer Gravity Gradient Instrument (GGI)
- B The GSS Operational Computer Program
- C GGI and Gravity Gradiometer System Definition Studies Program Final Summary Report
- D Calibration Techniques Report, GSS ADM Program
- E GSS ADM System Confidence (Acceptance) Test Document, GSS ADM Program

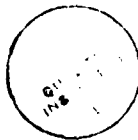
### Volume III - Book 1 Selected Sections of GSS ADM Prel Operating Manual

- 1.0 Introduction
- 2.0 System Installation
- 3.0 Installation Checkout
- 4.0 Calibration/Verification
- 5.0 DVOC Control Program Operating Instructions

### Volume III - Book 2 Selected Sections of GSS ADM Prel Operating Manual

- 6.0 Support Equipment
- 7.0 Replacement Parts Listing
- 8.0 Theory of Operation
- 9.0 Data Processing Flow Charts

### Volume IV - Classified Addendum



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## 1.0 INTRODUCTION

### 1.1 Background

Moving base gravity gradient instrumentation and gravity gradient systems have progressed significantly over the last few years to the present status where the six elements of the gravity gradient tensor are being measured at sea aboard the Navy Test Ship "NS Vanguard". The primary purpose of this Gravity Sensor System - Advanced Development Model (GSS ADM) is the measurement of the six elements of the gravity gradient tensor for real time deflection of the vertical correction of submarine inertial navigation systems gravity field (horizontal gravity anomalies). The deflection of the vertical is the largest remaining error mechanism of high performance inertial navigation systems and hence a driving function in weapon delivery accuracy of ICBM's.

The mechanization of a gravity correction system and a gravity mapping system is identical. In either case, the gravity vector is derived from the measured elements of the gravity gradient tensor. Gravity mapping is more accurate than real time determination of the gravity anomalies because post mission smoothing is possible using all measured data over an area and not just a single data point. The GSS ADM system makes provision for incorporating a dual channel gravimeter to aid in the determination of the magnitude of the vertical gravity vector.

A gravity mapping system consisting of a gravity gradiometer system, an inertial navigator and a gravimeter is illustrated in block diagram, Figure 1-1. Such a system will permit high speed, high accuracy surveys of the horizontal and vertical gravity components aboard a moving vehicle.

### 1.2 Objectives

The objectives of this Integrated Gravity Mapping System (IGMS) study program were:

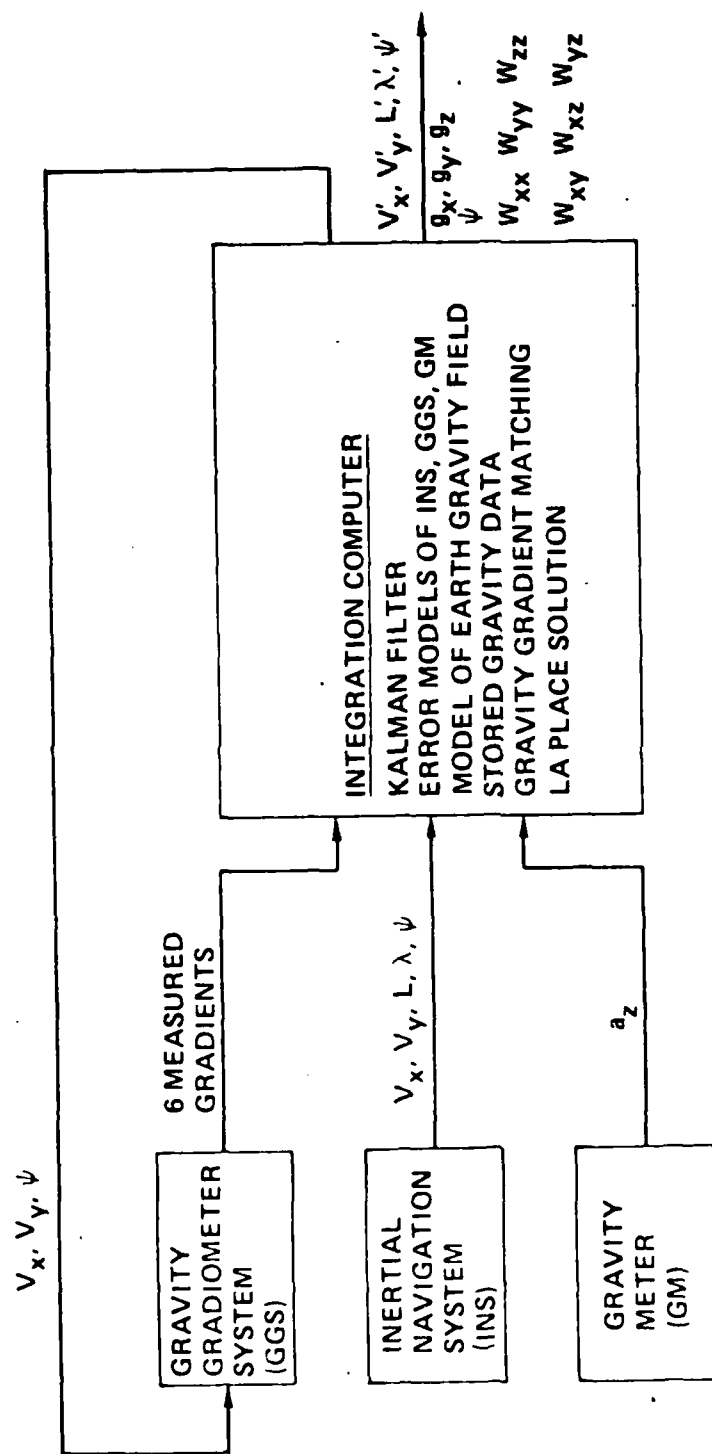


FIGURE 1-1. INTEGRATED VERTICAL DEFLECTION AND GRAVITY MEASUREMENT SYSTEM

- To generate a description and analysis of a moving base gravity mapping system for land based and airborne applications capable of producing gravity survey accuracies of better than 1.0 mgal or vertical deflection to better than 0.2 arc seconds. The detailed results of the study are sufficient to initiate design fabrication and test of such an integrated gravity mapping system.
- To utilize for the gravity mapping system, to the extent possible, the evolving hardware and software designs of the Advanced Development Model Gravity Sensors System (GSS ADM) currently being funded by the Strategic System Project Office (SP24) for the US Navy, under the management of Sperry Systems Management.

### 1.3 Scope

#### 1.3.1 General

The Integrated Gravity Mapping System (IGMS) study considered the above objectives and addressed the following topics:

- System Description/Functional Block Diagram
  - (a) Gravity gradiometer and gravimeter systems
  - (b) Inertial navigation system (INS)
  - (c) Digital computer
  - (d) Interfacing electronics
- Definition of Modifications to the ADM-GSS required for the Integrated Gravity Mapping System
  - (a) Based on error analyses
  - (b) Detailed areas
    - Hardware
    - Software
    - Changes dictated by environmental aspects
  - (c) Minimum modifications from current ADM GSS
- Definition of Mission Requirements
  - (a) Development of required accuracy as a function of vehicle speed, altitude, correlation distance and mission times and profiles.
  - (b) Identification of environmental disturbances including linear/angular accelerations and vibrations, temperature and magnetic fields.

- Error Analyses

- (a) Based on performance of the Advanced Development Model Gravity Gradiometer Instrument and the ADM GSS System.
- (b) Based on platform vibration isolation and temperature designs of the ADM GSS.
- (c) Environmental disturbances associated with the three classes of candidate carrier vehicles.
- (d) Mission scenarios.

### 1.3.2 Technical Report Organization

Section 2.0 summarizes progress and results to date. Also discussed are the topics requiring further investigations. Subsequent sections discuss in detail the principal findings under each major heading. To improve readability, descriptions of the mathematics of the Gravity Gradiometer have been placed in Appendix A and a detailed discussion of the computer algorithms in Appendix B. A copy of the Summary Test Report for the baseline GGI has been included as Appendix C, a copy of the GSS ADM Calibrations Techniques Report in Appendix D, and a copy of the Confidence/Acceptance Test document for the GSS ADM equipment is included as Appendix E. These appendices may be found in Volume II of this report.

Volume III contains selected sections of the GSS ADM Preliminary Operating Manual to indicate the status of the gravity sensor system.

Information in these additional volumes provide supporting material of the system described in Sections 3.0, 7.0 and 8.0 herein but are not required reading for comprehension of this report.

Performance data of the ADM GGI referred to in this report are classified CONFIDENTIAL. They have therefore been removed from the body of this report and replaced by the word "CONFIDENTIAL". All pages which have been expurgated in this fashion are reproduced in Volume IV which is then classified CONFIDENTIAL.

## 2.0 SUMMARY AND CONCLUSIONS

### 2.1 General

The Integrated Gravity Mapping System (IGMS) equipment was defined. The principal changes between the IGMS and the GSS ADM are: (a) selection of a new digital computer, (b) the substitution of an Airborne Inertial Navigation System for SINS, (c) redesign of the platform enclosures (binnacle) and its associated cooling system, and (d) the inclusion of a gravity meter. The conclusions are summarized as follows:

- 1) A modified version of the GSS ADM system, which is presently undergoing tests at sea aboard the NS Vanguard, will meet the requirements of the Integrated Gravity Mapping System (IGMS). The required modification primarily concerns environmental conditioning of the equipment, mounting of the platform from floor rather than ceiling, and substitution of shipboard computer and inertial navigation system for more suitable types for this application.
- 2) The candidates for inertial navigation systems and computers are in production and are available on a timely basis for the IGMS.
- 3) The deflection of the vertical and the vertical component of gravity can be established between two 0.75 milligal gravity tie points with an accuracy of 1.0 milligal using the demonstrated performance levels of the advanced development gravity gradient instrument (ADM GGI's). The gravity survey accuracy is relatively insensitive to distance between tie points (up to 100 km), number of ZUPTS, vehicle speed, and GGI noise.
- 4) Airborne gravity surveys can be achieved to an accuracy of 1.0 milligal over a 200 km by 200 km area with the demonstrated performance level of the ADM GGI's. For larger gravity surveys, the high frequency noise of the GGI's will require improvement.
- 5) An improvement of the ADM GGI noise level from  $25E^2/\text{rad/sec}$  to  $10E^2/\text{rad/sec}$  is believed readily achievable. The Model VII accelerometer noise is  $3E^2/\text{rad/sec}$  and the investigation to identify the noise contributors which increase it to  $25E^2/\text{rad/sec}$  have been limited in the past because it is of no consequence for the US Navy application. Noise in electronic circuits and wiring are prime suspects for this additive noise.

6) At this time slip ring cleaning is scheduled after 2500 hours of GGI operation. A rolling element slip ring assembly is under active development by Bell under IR&D funds with the objective of eliminating this requirement. This effort is progressing well.

7) The reliability experience based on two months continuous operation on the Navy Ship Vanguard has been excellent. No failures in the prime GSS ADM system hardware have occurred and the design modifications required as a result of the shakedown cruise have been minimal. GGI safety circuits had to be desensitized. The GSS ADM system was functionally operative within a week after delivery to the dock at Port Canaveral.

8) Provisions are made to mount a dual channel gravimeter (BGM 4) mounted, to the pitch gimbal of the GSS platform. Gravimeters augment long wave vertical gravity data.

9) A delivery schedule for an Integrated Gravity Mapping System installed in a land vehicle and an aircraft ready for turn-key operation in three years is deemed feasible because of the direct applicability of the extensive Navy GSS ADM program. For this reason it will be a low risk and relatively low cost approach to meet the AFGL/ADM objectives for an airborne and land vehicle high accuracy gravity mapping system.

## 2.2 Topics Requiring Further Investigations

- Refine binnacle layout to a higher detail level to incorporate the latest data for the selected INS and to reflect evolving cooling system and isolator concepts.

- Conduct final thermal analysis for the binnacle air cooling system.

- Prepare preliminary specification and obtain manufacturers comments and price/delivery quotes for candidate digital computers. This will be the basis for the final specification.

- Layout pallets based on platform layout and final computer and INS selections.



- Expand analyses defining missions for the land vehicle and aircraft scenarios.

- Conduct further error analyses to verify gravity anomaly and deflection of vertical errors to be expected from the mission scenarios.

- Expand analyses to determine sensitivities of gravity mapping errors to variations in gradiometer and gravimeter self generated noise.

Milestones achieved during this study include the following

- A preliminary layout of the modified platform concept was completed.

- The Honeywell AN/ASN-136 (SPN-GEANS) and the Litton LN-39 Inertial Navigation Systems (INS) have been selected as being suitable for this application, depending on the specific IGMS mission. The LN-39 system is adequate for limited area gravity mapping. The higher performance SPN GEANS will be required for large area airborne mapping missions. Honeywell, St. Petersburg, Florida, and Litton, Woodland Hills, Cal., have been contacted to supply in-field experience data for their respective systems. The principal criteria for selection between these two systems will be the mapping mission profile which is currently being defined by AFGL.

- The same navigator will be used for airborne and land vehicle missions to provide interchangeability.

- Performance data, operational instructions, dimensions and ROM costs were obtained for the candidate navigators.

- The candidate computers were narrowed down to either the ROLM MSE-14, or the Norden PDP-11/70M. Cost considerations will be paramount in making the final selection.

- A preliminary gravity mapping performance analysis was conducted for the transfer of the vertical deflection at points between two gravity tie points. The analysis using a statistical gravity model of the earth in combination with a least square collocation technique and various gravity gradiometer and gravimeter error models shows that the presently achieved gravity sensor system performance to be adequate for the mission with a considerable performance margin.

A preliminary airborne mapping accuracy analysis was also carried out based on the extension of single dimensional Wiener smoothing of a statistical gravity model, a specified flight pattern and various gravity gradiometer error models. This analysis also indicates that the presently achieved gravity sensor system performance to be adequate for the mission with a considerable performance margin. A two-dimensional airborne gravity mapping performance analysis is currently being formulated.

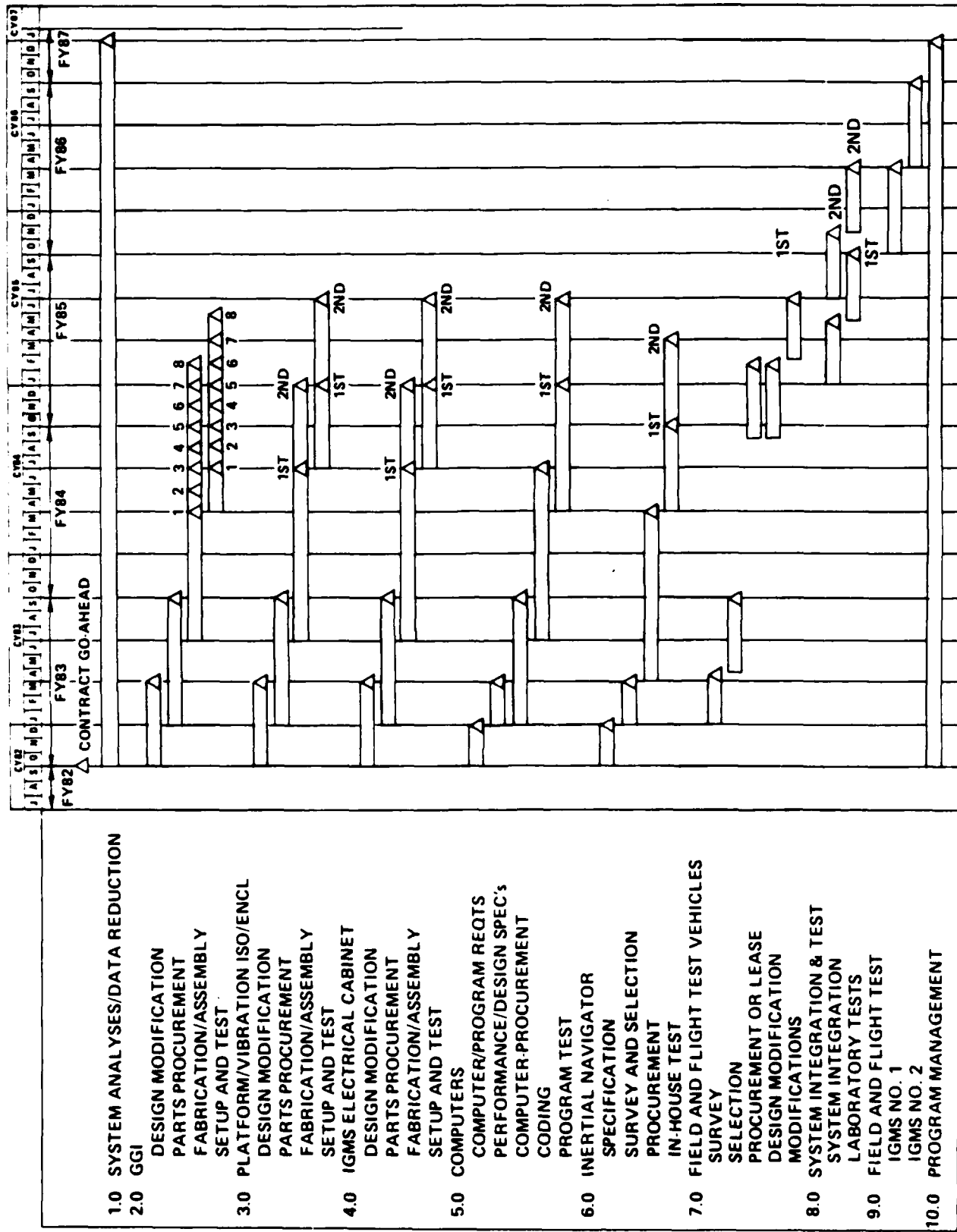
- Library searches, INS manufacturers and helicopter manufacturers were contacted along with one company involved with vehicle testing to solicit environmental data. Linear accelerations below 1 Hz were of potential concern because of GGI sensitivities in this region. It was concluded that the expected acceleration levels in this frequency band would not significantly deteriorate system performance with the current sensitivities. The ongoing GGI improvement program is expected to further reduce these sensitivities.

### 2.3 Program Plan - Integrated Gravity Mapping Systems

A summary program plan for the delivery of two (2) integrated gravity mapping systems, one each installed on a land vehicle and aircraft, respectively, is illustrated on Figure 2-1. A go-ahead date of October 1, 1982 has been assumed as an example only. Should the starting date differ, the delivery dates would vary accordingly. The overall schedule could be shortened six months by removal of contingencies and a more intensive effort should this be desirable.

The program plan outlined on Figure 2-1 incorporates the experiences gained on the GSS ADM system for Sperry/SSPC/USN, which was delivered and installed on the Navy Ship Vanguard approximately two years after go-ahead. Procurement of parts and components took more time than the six months estimated for that program resulting in intensive expediting and consequent heavy overtime use to recover schedule. The outlined program allocates nine months for parts and component procurement for this reason. It is a realistic schedule allowing for unexpected problem areas and time delays.

FIGURE 2-1. SCHEDULE



1) End Item Delivery

The end items are two Integrated Gravity Mapping Systems, one each installed on a land vehicle and aircraft, ready for turn-key operation. Delivery will be after six months of field testing in March and September of 1986, respectively.

2) Program Plan Organization

The program plan contains ten parallel activities which will also serve as the model for the cost breakdown structure as follows:

- 1.0 System Analysis and Data Reduction
- 2.0 Gravity Gradient Instruments
- 3.0 IGMS Platform/Vibration Isolation System/Enclosure
- 4.0 IGMS Electronic Cabinets
- 5.0 IGMS Computer
- 6.0 Inertial Navigator System
- 7.0 Land Vehicle and Aircraft for IGMS
- 8.0 System Integration and Test
- 9.0 Field and Flight Testing
- 10.0 Program Management

A project engineer will be assigned to each of the first seven activities and will be responsible for technical, fabrication, test, product assurance, and fiscal accounting.

1.0 System Analysis/Data Reduction - System analysis and data reduction is an ongoing activity throughout the program. In the early phases, the requirements of subsystems will be defined in conjunction with the project engineers. Realism as to what can be achieved with proven, reliable equipment will be an important factor in the decision making processes. Tradeoff studies of various mission scenarios will be discussed with AFGL/DMA since these are key in defining the hardware and software implementation. Toward the latter phase of the program, analysis of laboratory and field IGMS data will become the major activity. Close liaison and consultation with AFGL/DMA and associated organizations such as the Aerospace Center in St. Louis and TASC will take place to assure that optimum methods of deriving the gravity information from measured data is used.

2.0 Gravity Gradiometer Instruments (GGI's) - Eight gravity gradiometers will be fabricated, assembled and tested - three GGI's and one spare for each system. The GGI configuration for the IGMS application will be defined, as results of performance improvement and simplification efforts which are currently in progress, and will continue through March 1983. The envisioned modifications to the ADM GGI are outlined in Section 6.0 of this report and concern design details rather than concept changes. Nine months are allocated to parts and component procurement - nine months for fabrication and assembly followed by a three months set-up and test period. The extensive fabrication and test equipment developed for the GSS ADM program will be available for this program. Detail build plans and test procedures will be submitted to AFGL for information prior to initiation of activities.

3.0 IGMS Platform/Vibration Isolator/Environmental Enclosure - Two platform/vibration isolators/environmental enclosures will be fabricated with spare parts and components for field support and repair. The additions and modifications to the GSS ADM platform will be designed and detailed by the end of March 1983. These modifications and additions are primarily concerned with floor mounting of the platform assembly and inertial navigator to a common plate. A revised vibration isolation system for this new arrangement will be subcontracted to MRAD Corporation in Boston. These are briefly discussed in this report. Assembly and wiring of the platform will start in July 1983. While the two platforms are scheduled six months apart, operations could be carried out for the two platforms at the same time if more efficient. After assembly of the platform but prior to the installation of the GGI's or the inertial navigation system, a set up and test program will be conducted using a platform test set. The platform test set contains all the electronics to gyro stabilize the IGMS platform, synchro cage and erect to the platform with accelerometers. Detailed build plans and test procedures will be established and submitted to AFGL for information prior to initiation of activities.

4.0 IGMS Electronic Cabinets - Two sets of electronic cabinets will be fabricated and tested with sufficient spare modules and power supplies for field maintenance. On-board NS Vanguard experience of the GSS ADM will be factored into setting sparing requirements. The detail design modifications will be completed by the end of March 1983. As outlined in this report, these will be primarily concerned with the interface buffer drawer because of the

use of a smaller militarized computer. Improvement observed as a result of efforts conducted under the Sperry/SSPO program will be incorporated, schedule permitting. A nine month period for part procurement has been allocated. Very long lead items such as connectors will be ordered on a timely basis. One year is set aside for fabrication and test of the electronic boards and modules, for fabrication and assembly of the electronic drawers and for fabrication of the cabinets. Debugging of the electronic drawers and cabinets will be completed in December 1984 for the first system followed by the second system six months later. Detailed build plans and test procedures will be submitted to AFGL for information.

5.0 IGMS Computers - Three computers will be purchased for the two IGMS systems and one spare. The spare computer will also be used for data reduction at Bell. The selection of the computer as outlined in this report will be made by December 1982 and a procurement specification written. Nine months is allocated for procurement of the computers. The performance and design specifications will be completed at the end of September 1983 and form the basis of element by element coding. Software test will be completed December 1984 for the first system and June of 1985 for the second. The land vehicle and aircraft IGMS computer programs may be different in some aspect.

6.0 Inertial Navigation System - The specification for the inertial navigation system will be completed by the end of 1982 and a selection of the candidate manufacturer made in consultation with AFGL/DMA by March 1983. After delivery of the inertial navigators, a six month test period for familiarization, interfacing and performance evaluation is provided. The possibility of a service contract with the inertial navigator contractor will be explored.

7.0 Land Vehicle and Aircraft for IGMS - A survey of candidate land vehicles and aircraft for the gravity mapping systems will be conducted early in the program. Availability, acquisition or leasing cost, operation cost, dynamic characteristics, etc. will be among the factors scrutinized during the first three months of the program. From these data, the preferred land vehicle and aircraft will be selected in September of 1983. This endeavor may include acceleration measurements aboard the vehicle and aircraft under various conditions. Structural drawings will be obtained for an initial assessment

of installation problems made. AFGL/DMA will be consulted prior to making a final determination of the selected vehicles. The procurement or leasing of the selected vehicles will take place during the six month period starting in September 1984. Detail design of installation hardware and auxiliary equipment will be conducted in parallel while the vehicle and aircraft is being procured. Preparation of the vehicles will be completed at the end of June 1985.

8.0 System Integration and Test - At the end of December 1984, all subsystems of IGMS No. 1 will be available for integration and test. A four month period for integration followed by a four month period for system evaluation in the laboratory have been allocated. Eliminating wiring errors, ground loops and EMI will be a major activity during integration. Lab evaluation will include dynamic testing on the Scorsby for repeatability requirements and turn-on transients and performance.

9.0 Field and Flight Testing - A six month field test program for the land vehicle system and a six month flight test program for the aircraft system are deemed sufficient. The preference over which program should take priority will be mutually agreed by Bell and AFGL/DMA. One month will be devoted to installation and functional set-up of the IGMS in the respective vehicles, two months for shakedown of the systems in the land vehicle and aircraft in the Niagara Frontier Area followed by three months operation over designated calibrated gravity areas.

#### 2.4 Contributing Engineers

The following Bell Aerospace Textron Engineers have contributed to the work reported in this document:

C. Affleck	J. Hutcheson	W. Rusnak
C. Beaumariage	A. Jircitano	
A. Dickman	E. Metzger	
A. Edwards	L. Pfohl	

### 3.0 DESCRIPTION OF THE GSS ADM SYSTEM

#### 3.1 General

The Integrated Gravity Mapping System (IGMS) equipment complement is based on the design of the shipboard Advanced Development Model Gravity Sensors System (GSS ADM) built for SP 24 USN under the management of Sperry Systems Management Division. This equipment has recently been delivered to the US Navy and has been installed aboard the Naval Test Vehicle USNS Vanguard for a period of at sea testing.

The GSS ADM system which will be slightly modified for the IGMS application consists of a three-axis platform stabilizing a triad of gravity gradiometer instruments (GGI's) and a set of electronic cabinets housing the off-platform electronics and a digital computer for platform control, data processing, recording and interfacing.

The major units of the GSS ADM systems are:

- (a) Ship's Inertial Navigation System (SINS) - Available on board the Naval Test Vehicle
- (b) Dedicated VAX-11 Operational Computer (DVOC) - Government Furnished Equipment
- (c) Two Gravity Gradiometer Electronic Cabinets (GGEC's)
- (d) Platform Enclosure (Binnacle)
- (e) Gravity Sensor Platform (GSP)
- (f) Shock Vibration Isolators
- (g) Coolant System
- (h) Gravity Gradiometer Instruments (GGI's)

Three gravity gradiometer instruments (GGI's) are mounted at an umbrella angle of approximately 35.26 degrees from the horizontal in a north-east-vertical down coordinate system. The platform (GSP) is housed in the platform enclosure (binnacle, or shroud) for environmental conditioning. Two electronic cabinets (GGEC's), housing twelve drawers organized along functional lines contain the off-platform electronics to operate the platform and gravity gradient instruments, provide monitoring and control functions and incorporate the interface buffer to the computer. The computer is a government furnished, commercially available Digital Equipment Corporation (DEC) VAX-11/780 computer which executes the algorithms to convert raw gravity gradient measurements of



the three GGI's into corrected gravity gradient tensors in the north-east-vertical down (NED) coordinate system. It also interfaces the gravity gradiometer system with the on-board ship's inertial navigation system (SINS) through an on-board "buffer computer" called the Central Data Monitoring System (CDMS).

The ADM GSS subsystems, which will be adapted for the IGMS, are shown in the photographs, Figures 3-1 through 3-12. Figure 3-1 is an external view of the GGI and Figure 3-2 is the ADM GGI in its shipping container. The interior physical assembly and components of the ADM GGI are shown in Figure 3-3. Figure 3-4 shows the platform with gimbal axes tilted to show one of the GGI's. The interior physical arrangement is shown in Figure 3-5. Figure 3-6 again shows the platform. In this figure, the gimbal angles are orthogonal. The two rectangular enclosures on top show the gravimeter locations. Another view showing the on-platform electronic module is shown in Figure 3-7. Figure 3-8 shows the platform enclosure (binnacle) mounted to a two axis motion inducing table (CARCO) for evaluation and testing of the system in a motion environment. The platform is within the enclosure. Clearly shown is an isolators assembly which provides attenuation to external linear and angular vibrations. The isolators are arranged to be at the vertices of an equilateral triangle. The third isolator is behind the binnacle in this view. Figure 3-9 shows the same arrangement but with the binnacle shrouds removed, showing the platform. Figure 3-10 shows GGEC #1. This rack provides the control and monitor functions for the three GGI's. Figure 3-11 shows GGEC #2. This rack provides the controls and monitors for the platform as well as the electronic interface buffers which communicate between the digital computer (DVOC) and the GSS systems. Shown along side the GGEC #2 rack is an auxiliary synchro digital readout which displays the actual platform gimbal angles. A strip chart recorder rack, shown in Figure 3-12 is also delivered as on-line monitoring equipment for the GSS ADM systems.

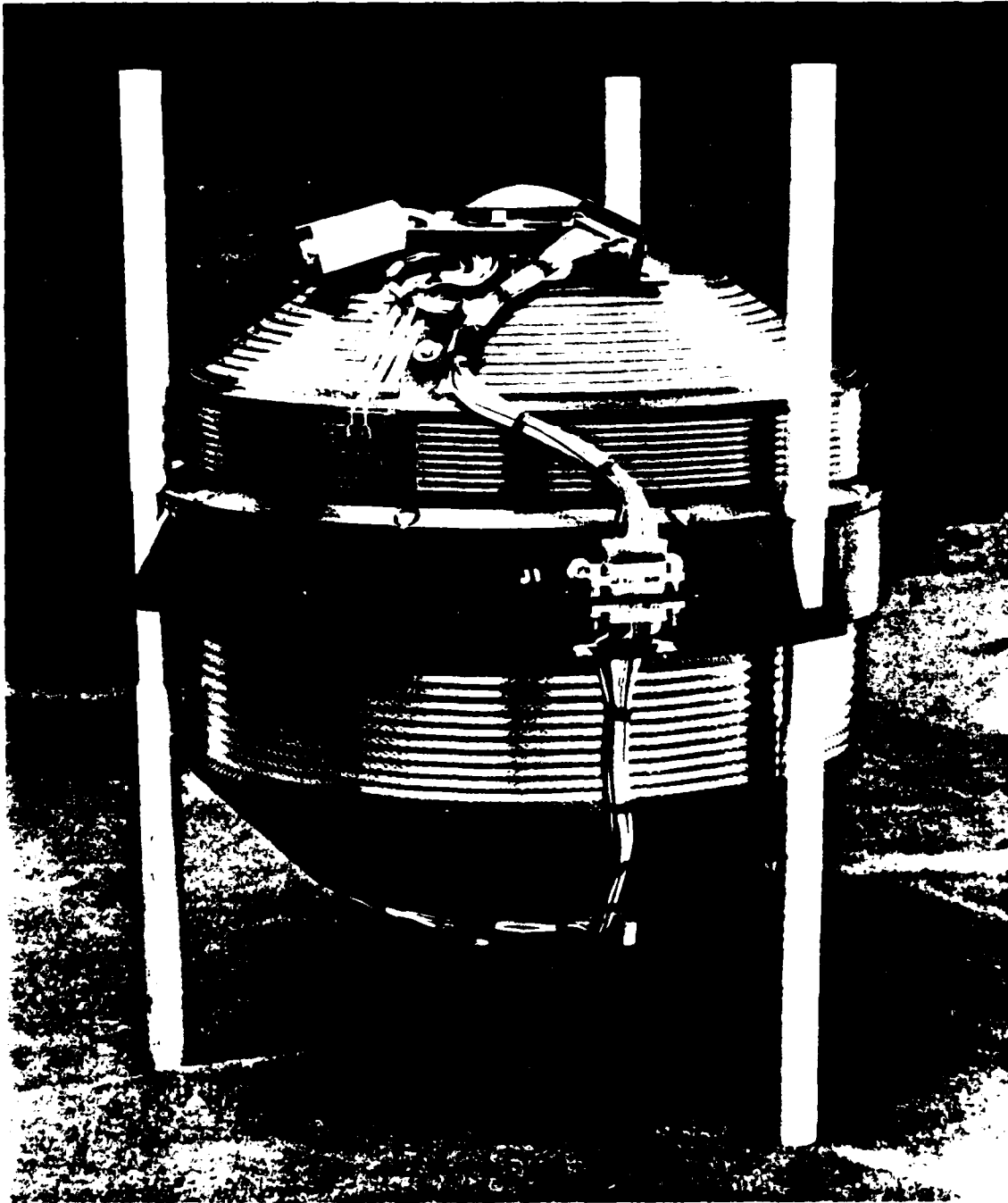


FIGURE 3-1. ADM GGI

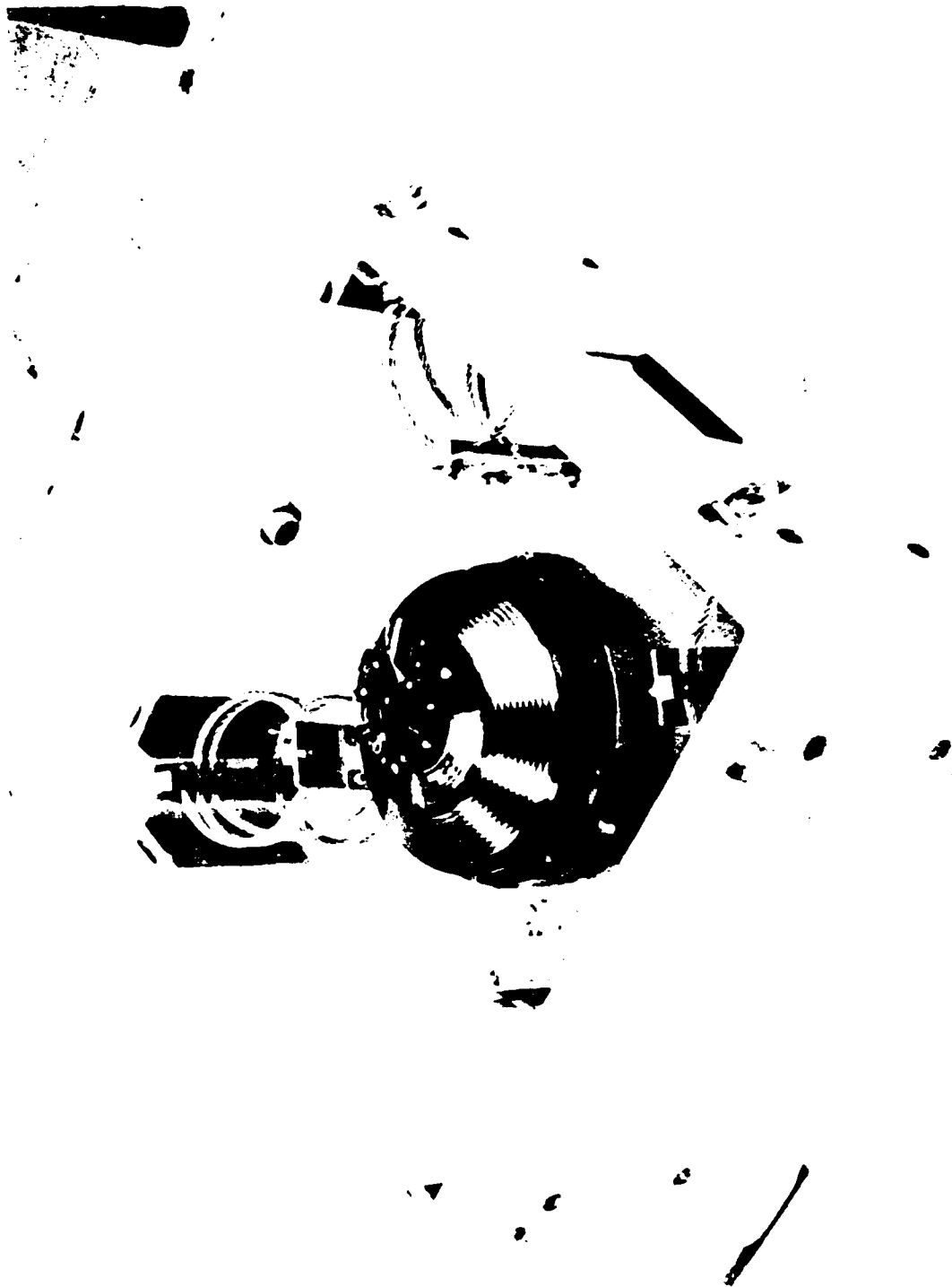


FIGURE 3-2. ADM 661 IN ITS SHIPPING CONTAINER

FIGURE 3-3. AF/GGI

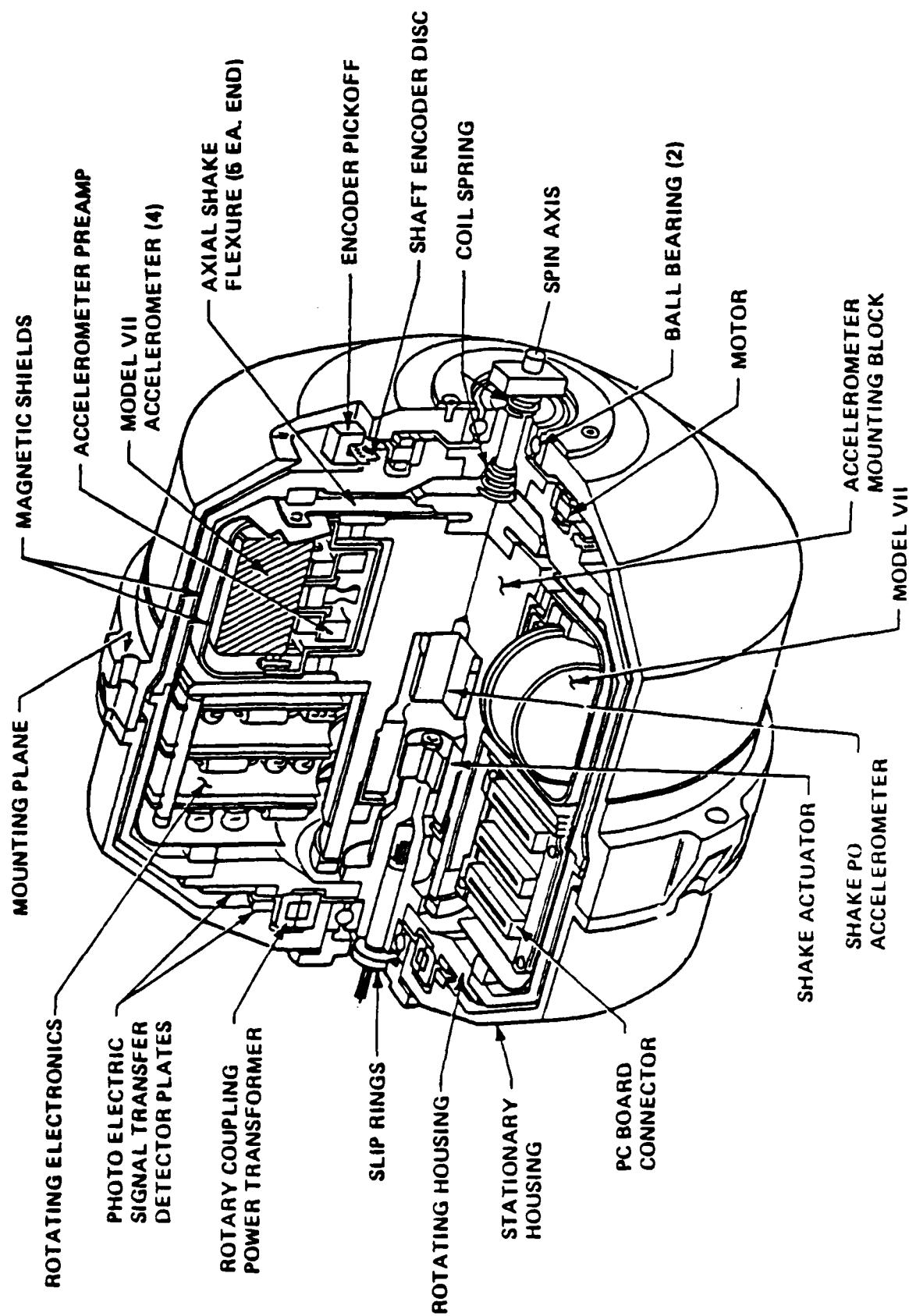
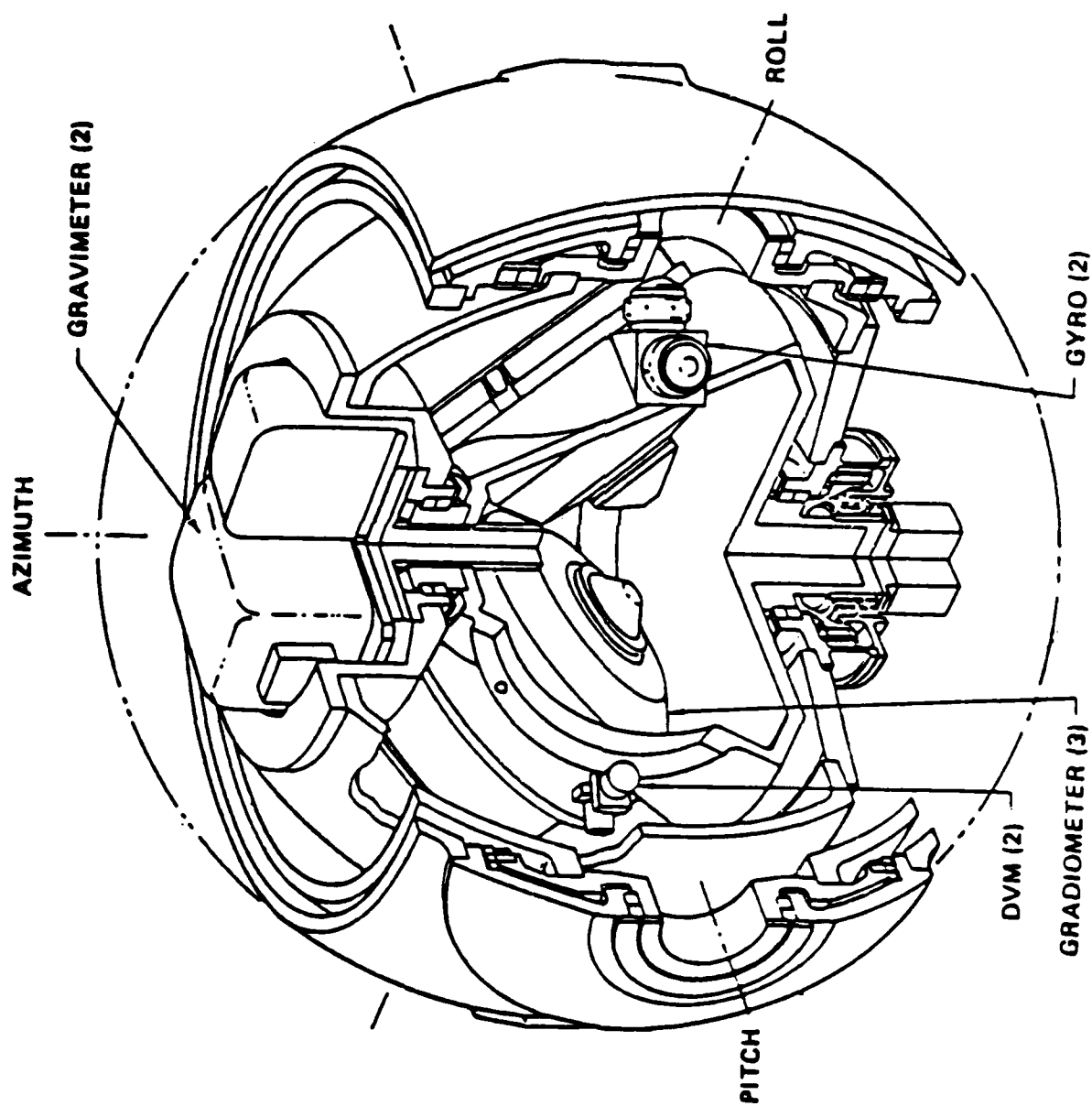




FIGURE 3-4. GSS ADM PLATFORM WITH GGI IN VIEW

FIGURE 3-5. STABILIZED PLATFORM



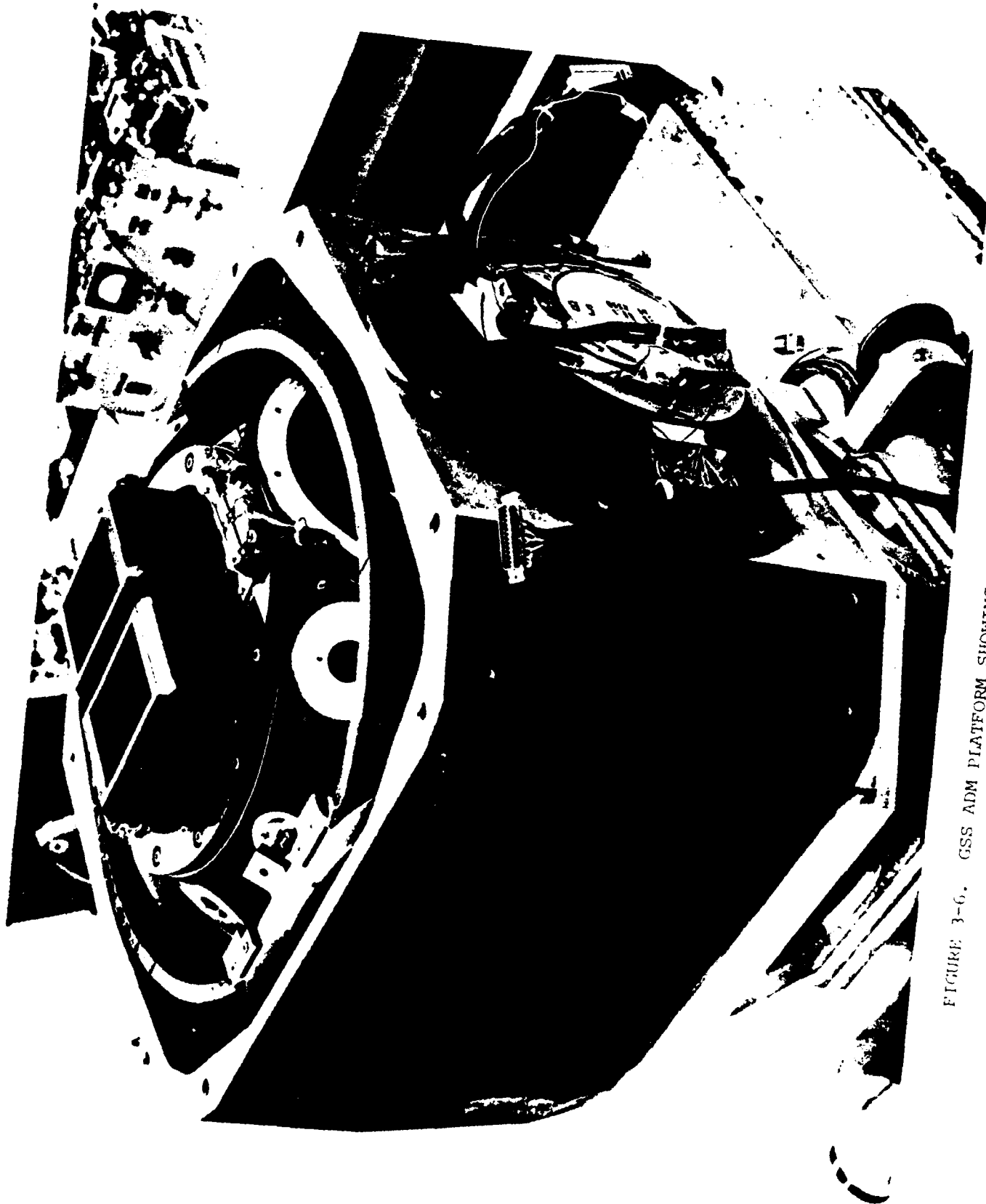


FIGURE 3-6. GSS ADM PLATFORM SHOWING LOCATION OF GRAVIMETERS



FIGURE 3-7. GSS ADM PLATFORM SHOWING ON-PLATFORM ELECTRONICS



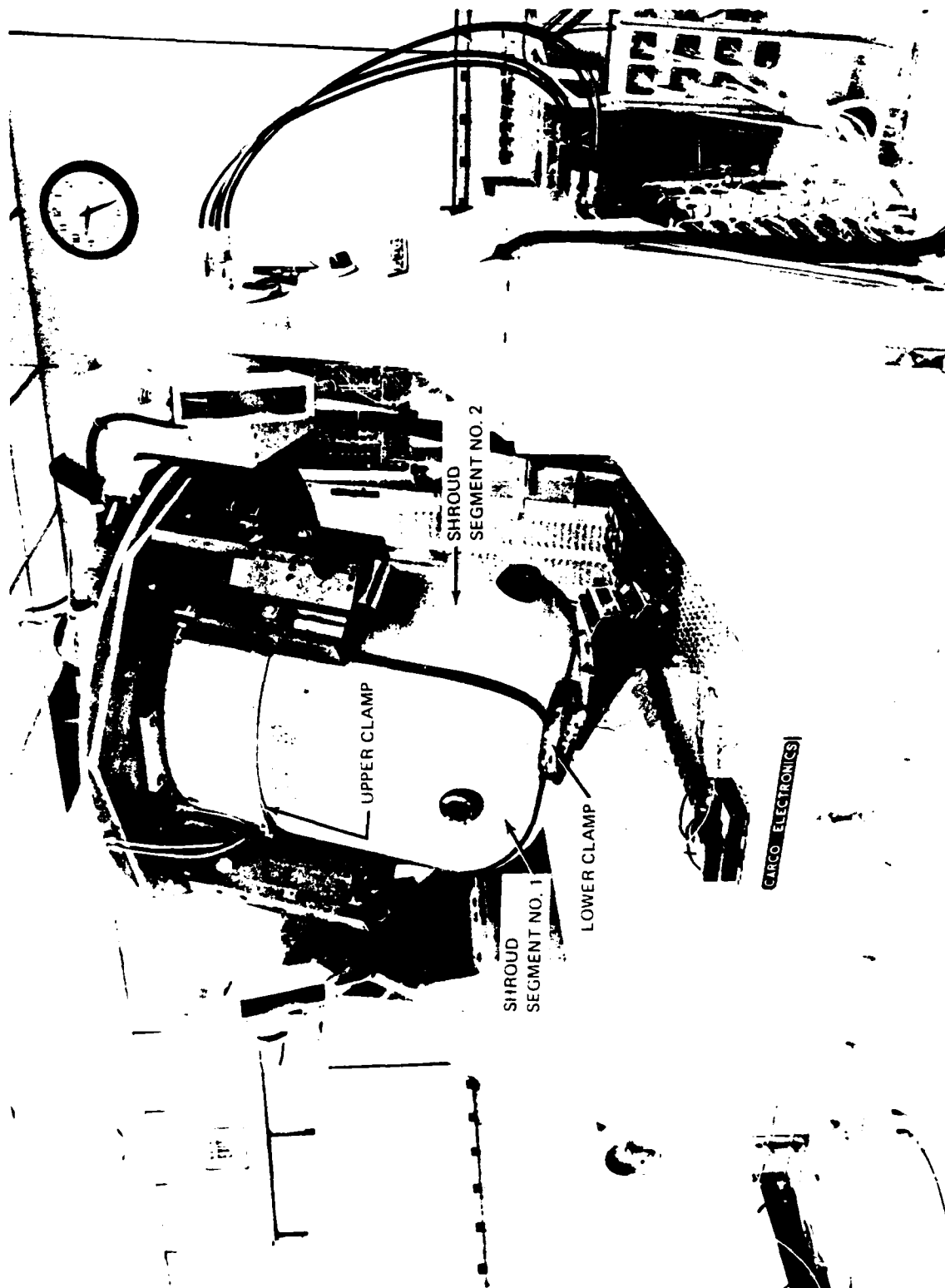


FIGURE 3-8. GSS ADM PLATFORM/BINNACLE ON SCORSBY TABLE

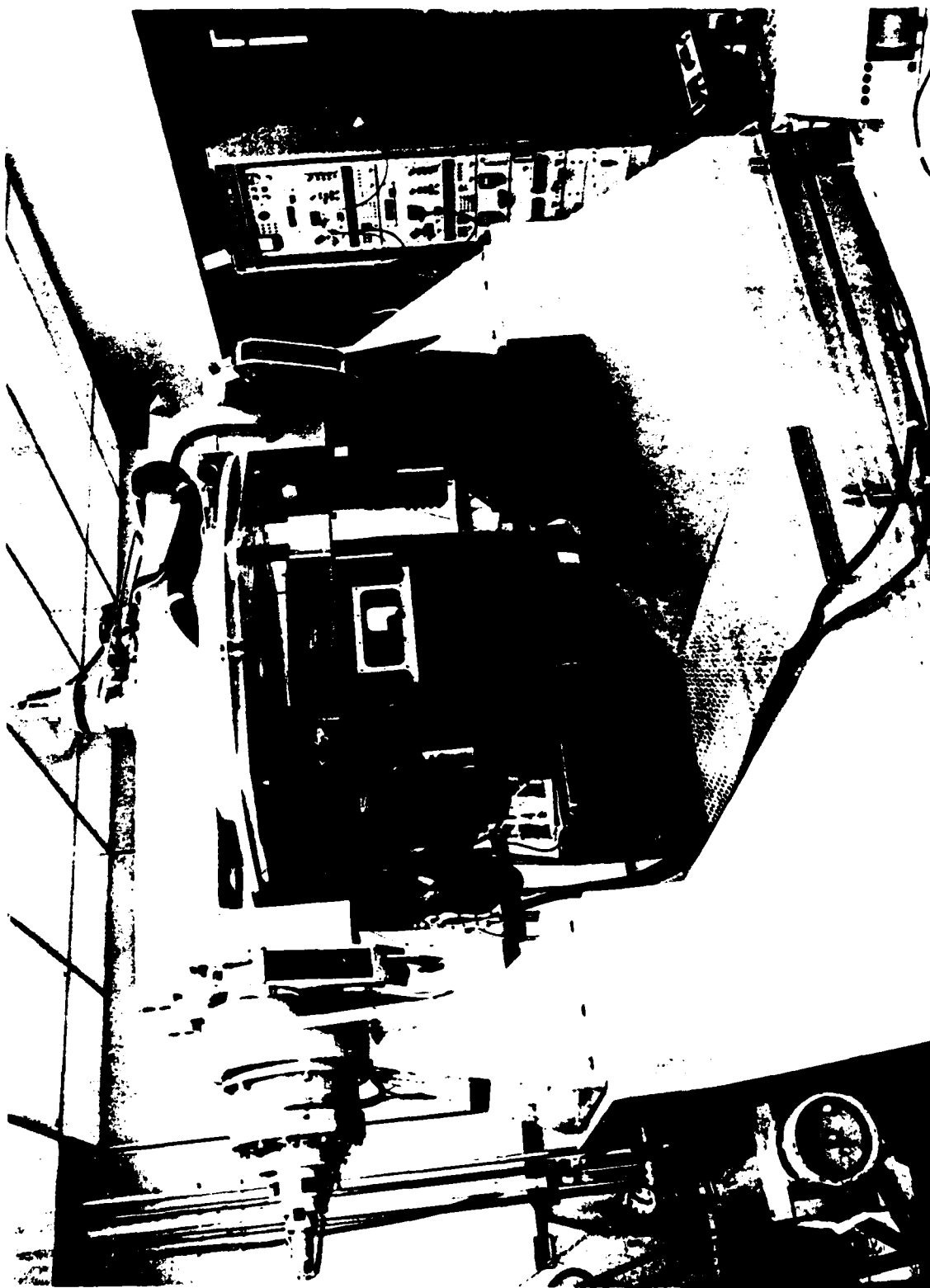


FIGURE 3-9. GSS ADM PLATFORM ON THE SCORSBY WITH BINNACLE/SHROUDS REMOVED

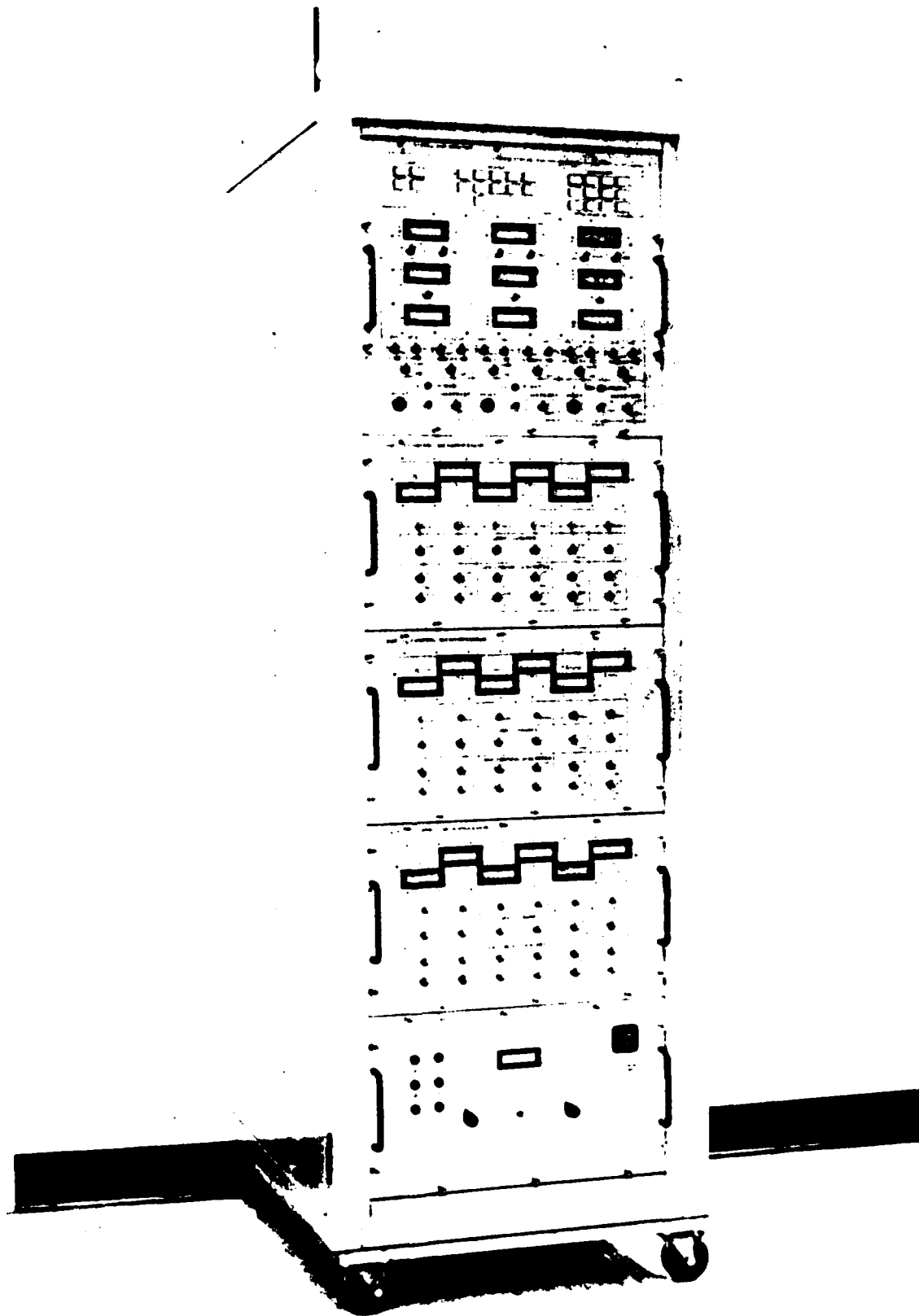


FIGURE 3-10. GSS ADM GGEC NO. 1

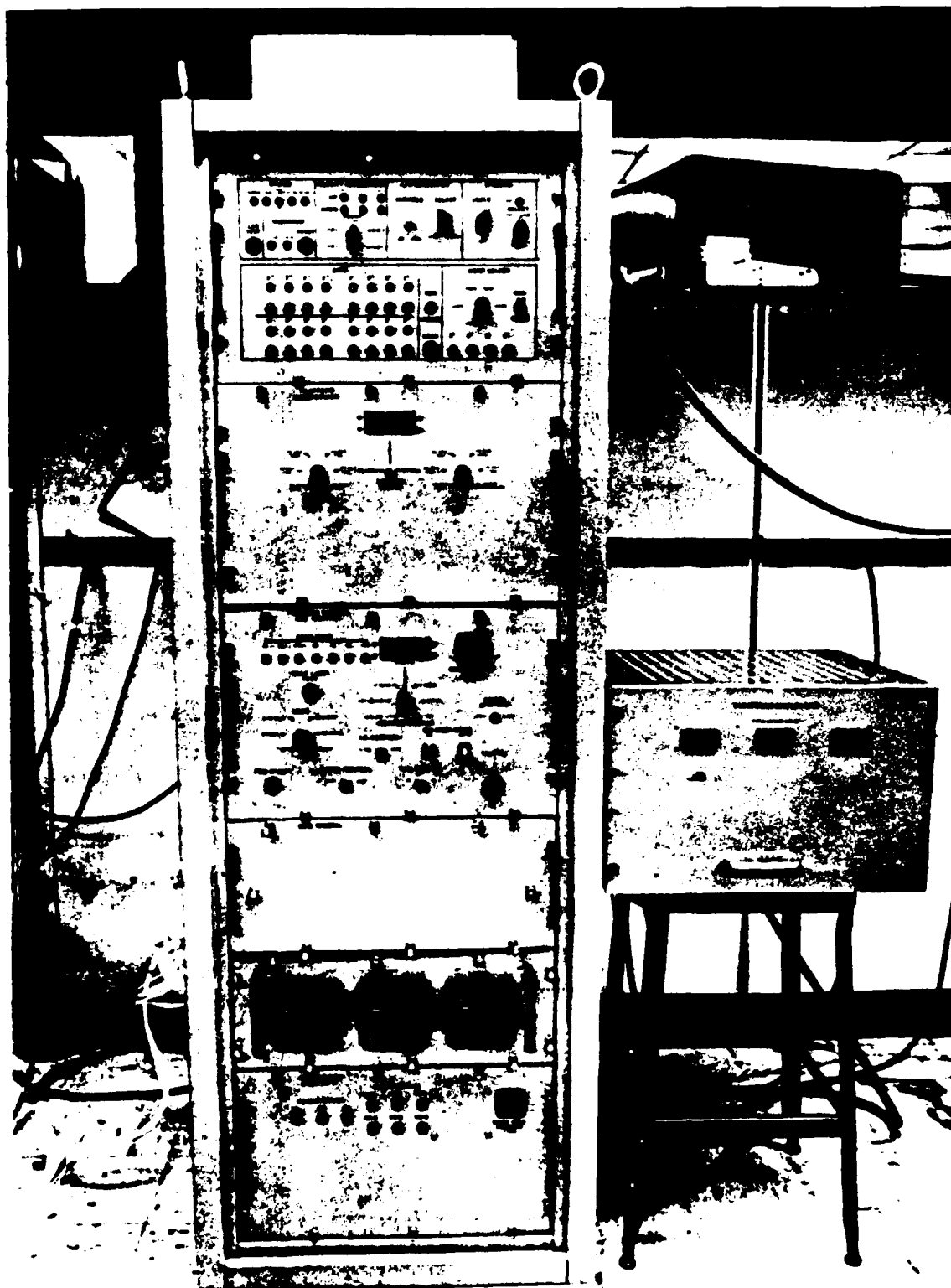


FIGURE 3-11. GSS ADM GGEC NO. 2

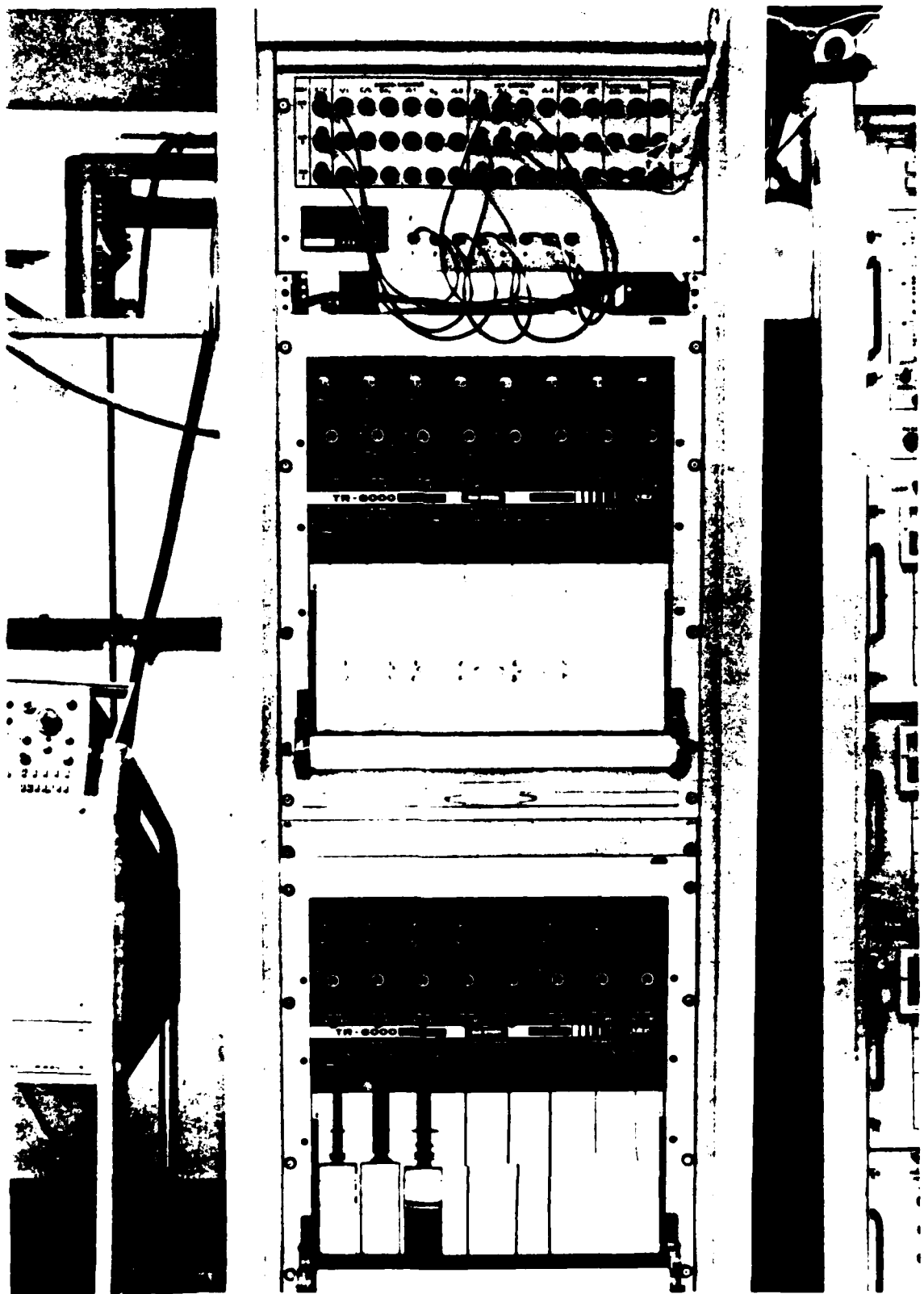


FIGURE 3-12. STRIP CHART RECORDER

The major units described above interconnect to form the GSS ADM system as shown in block diagram form in Figure 3-13A. The blocks illustrated in this figure list the subsystems contained in each major unit. These subsystems are described in more detail in the following paragraphs. The signal flow between the major units (blocks) of Figure 3-13A is further detailed in the functional and signal flow block diagram of Figure 3-13B, and a list of the functions of each of the subsystems contained in each major unit is also included. The layouts of these two figures are the same to allow easy correlation of the functions and subsystems.

A more detailed functional block diagram is also shown in Figure 3-14. This block diagram also illustrates the partitioning concept used in the GSS-ADM. Those electronic subsystems requiring relatively high frequency responses, and those particularly sensitive to slip ring noise were located as close to the signal source as possible, i.e., within the binnacle. The remaining electronics were located in the electronic cabinets. Thus, the speed control and axial shake control electronics for the GGI's, the gyro constraint electronics, the accelerometer electronics and the binnacle temperature controller were all installed on the platform (within the binnacle). The remaining electronics including the GGI loop control microprocessors, platform electronics and the computer interface electronics were located in the two electronic cabinets. The data processing subsystem (DVOC) was similarly remotely located. The following glossary of abbreviations used in Figures 3-13 and 3-14 is given below.

DVOC	Dedicated VAX-11/780 Operational Computer
GGEC 1	Gravity Gradiometer Electronic Cabinet 1
GGEC 2	Gravity Gradiometer Electronic Cabinet 2
GGIB	Gravity Gradiometer Instrument Buffer
CDMS	Central Data Monitoring System

SINS	Ship's Inertial Navigation System
LCMP	Loop Control Microprocessor
$\Sigma\alpha$	Sum of GGI Accelerometer Signals
BP	Band Pass Amplifiers/Filters
MUX	Multiplexor, Multiplexed
P,R,AZ	Pitch, Roll, Azimuth
STAB	Stabilization
$\Delta V_x, \Delta V_y$	Incremental Computed Velocities
BIN	Binnacle
HDNG	Heading
CAL	Calibration
GRAV	Gravimeter
LAT	Latitude
LONG	Longitude
VEL	Velocities

Detailed descriptions of each of the major subassemblies are given in the following subsections.

### 3.2 Ship's Inertial Navigation System (SINS)

The Ship's Inertial Navigation System (SINS) provides continuous position and velocity information and ship's attitude angles. In the GSS ADM system North velocity, East velocity and ship's heading (azimuth) angles are used to level and align the Gravity Sensor Platform (GSP).

The GSP has its own leveling accelerometers. However, as currently configured, the platform is not self-aligning. The azimuth synchro information from the SINS is used to North align the GSP; i.e., the GSP azimuth is synchro slaved to the SINS. Also, since the GSP is controlled by operating it as a navigator with the navigation equations being solved in the dedicated VAX-11/780 operational computer (DVOC), velocity updates from the SINS are used to trim out platform tilt errors and fine trim the alignment. Note that for the IGMS, the selected INS replaces the SINS navigator in the ADM GSS.

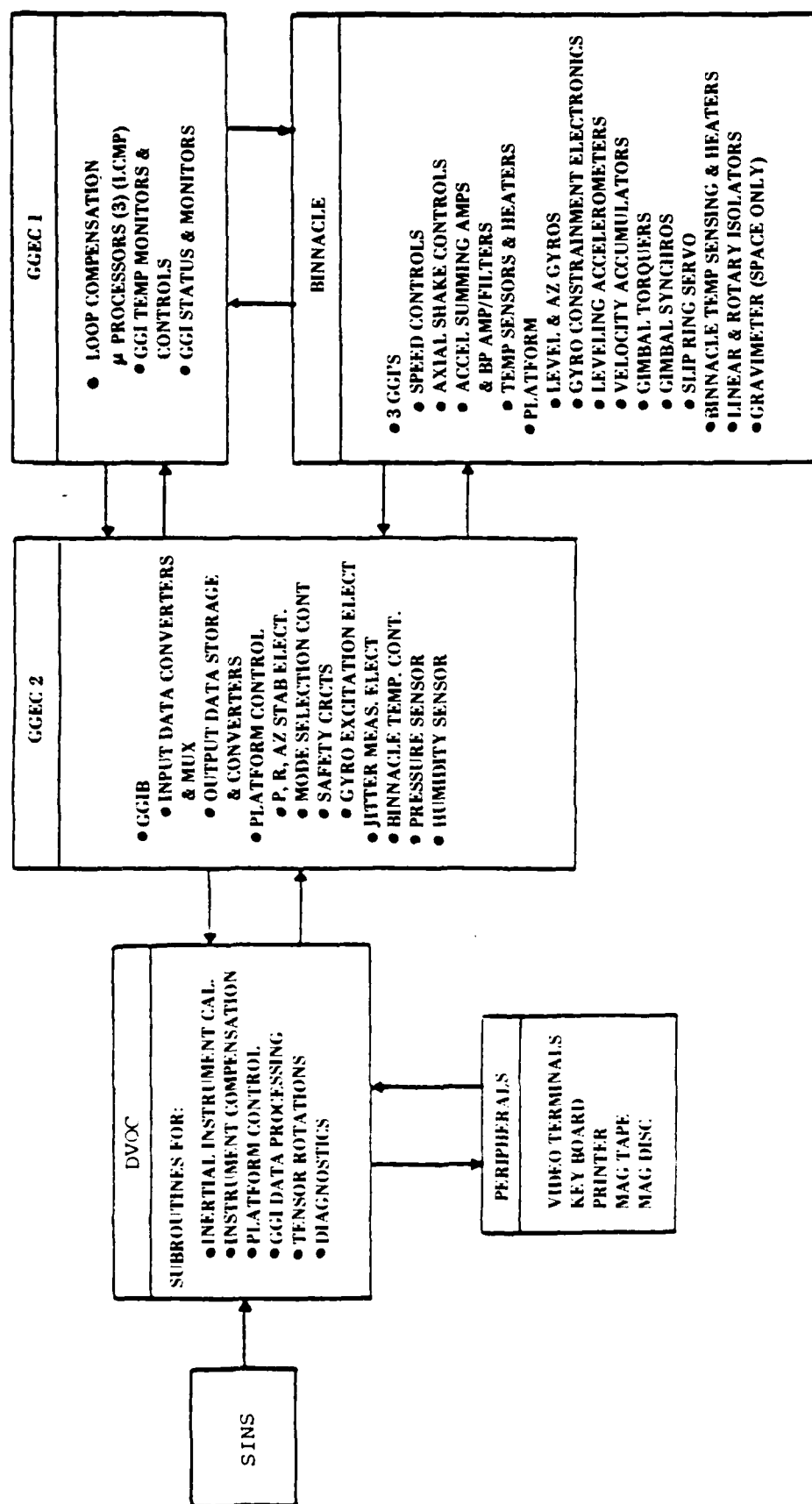


FIGURE 3-13A. GSS ADM SYSTEM



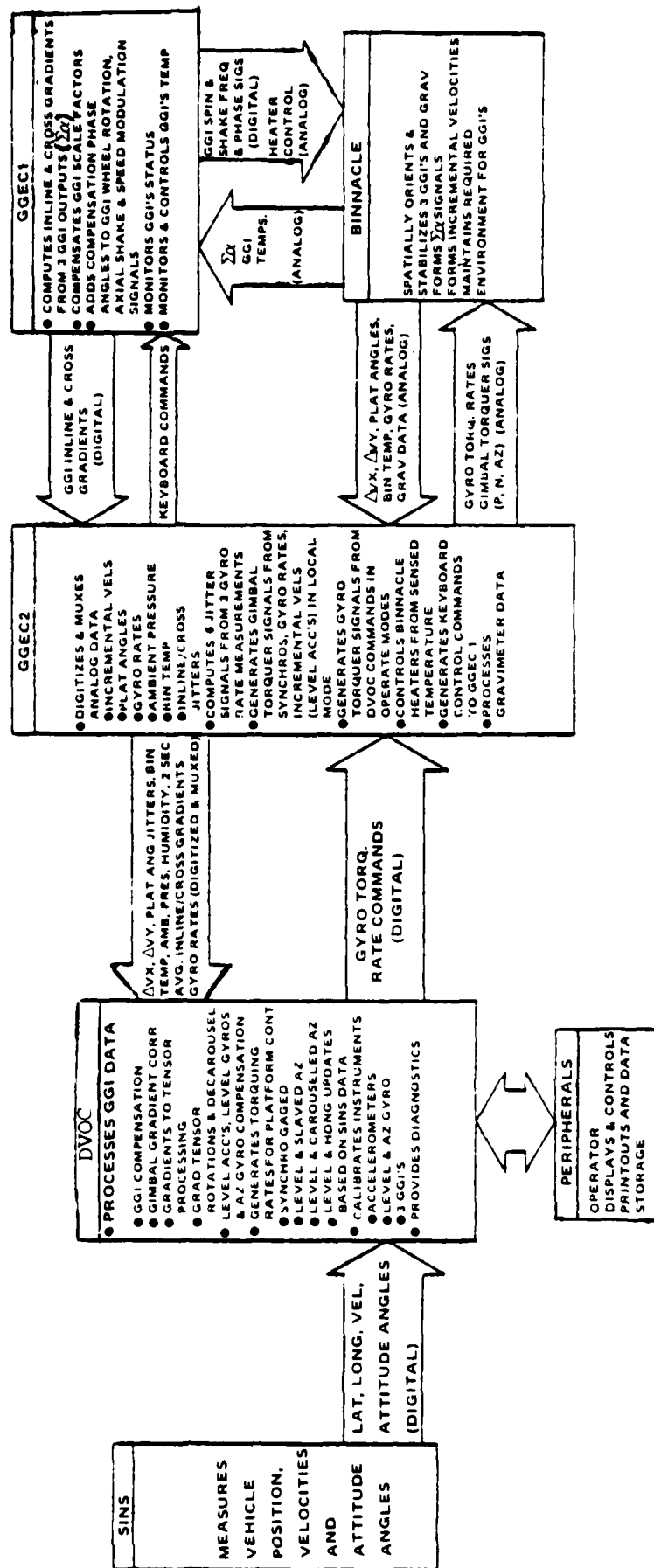


FIGURE 3-13B. SIGNAL FLOW DIAGRAM

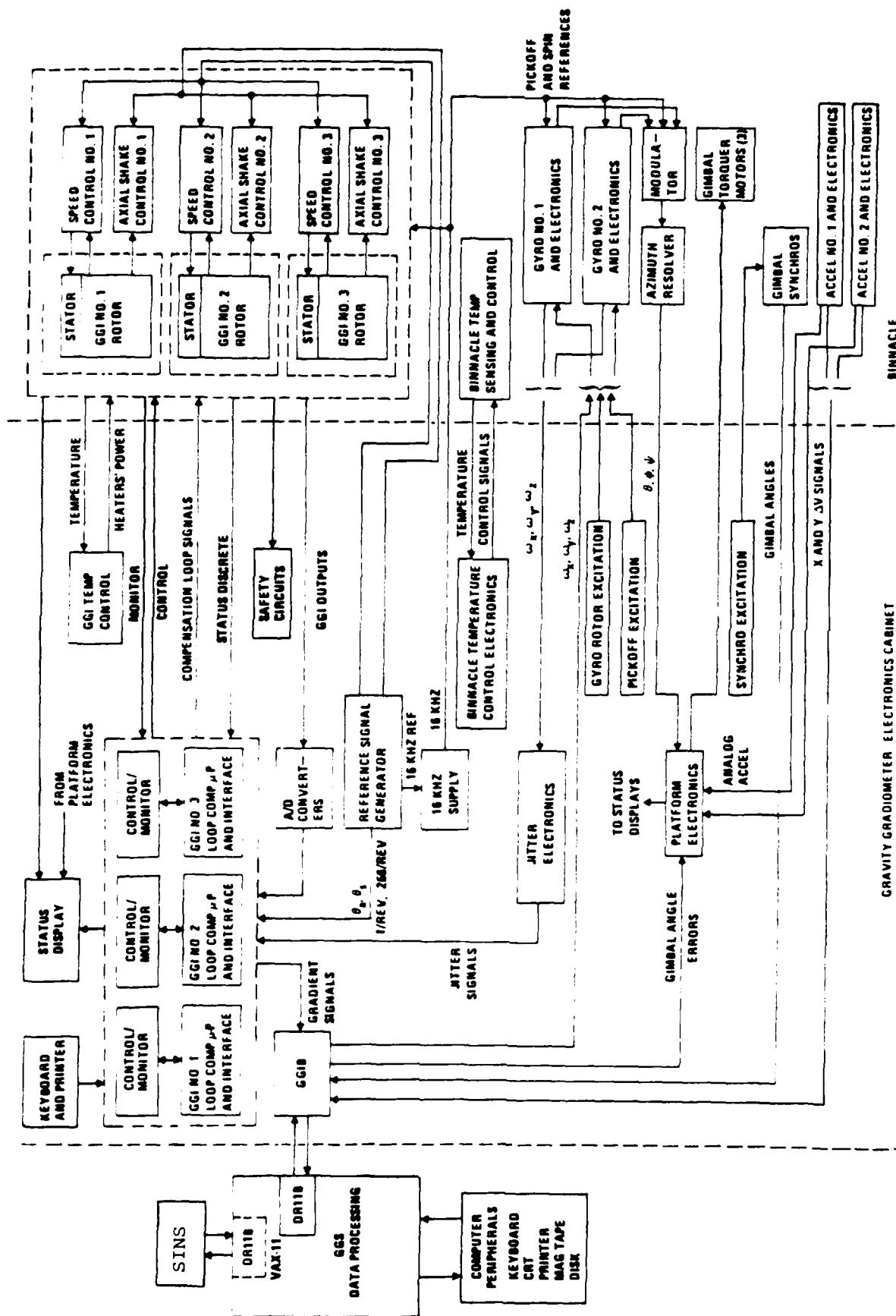


Figure 3-14. GSS Functional Block Diagram

### 3.3 The Gravity Gradiometer Electronic Cabinets (GGEC's)

#### 3.3.1 Introduction

All the electronics for the ADM GSS system, with the exception of those installed on the platform itself, are contained in two electronic cabinets as illustrated in Figure 3-15. The two cabinets, referred to as GGEC #1 and GGEC #2 are differentiated by their basic functions. GGEC #1 essentially controls the GGI's, whereas GGEC #2 basically controls the platform, formats and exchanges data with the DVOC. The main features of these cabinets are:

- The GGEC's are two modified, purchased, high quality cabinets of proven design and totally adequate for ship board application.
- All the electronics are mounted in drawers along functional lines. An inherent advantage of this approach is that drawers can be checked out in parallel without interference with GGI's, platform and computer activities.
- All the electronic circuits are packaged in SEM's except for the microprocessors and A to D and D to A converters and power supplies.
- GSS mode control is primarily manual with simple check lists. A visual monitor is provided for decision making. Care has been exercised in the switch layouts.
- The GSS can be fully operative with the electronic cabinets without the use of the dedicated VAX 11/780 operational computer (DVOC). The VAX 11/780 computer handles all the data processing, recording and interface computations with SINS.
- The cooling for the GGEC's is by forced air for the microprocessors, power supplies and miscellaneous electronics, and cold plate for SEM's.

The drawers of each GGEC are also organized along functional lines as shown in Figure 3-15 as follows:

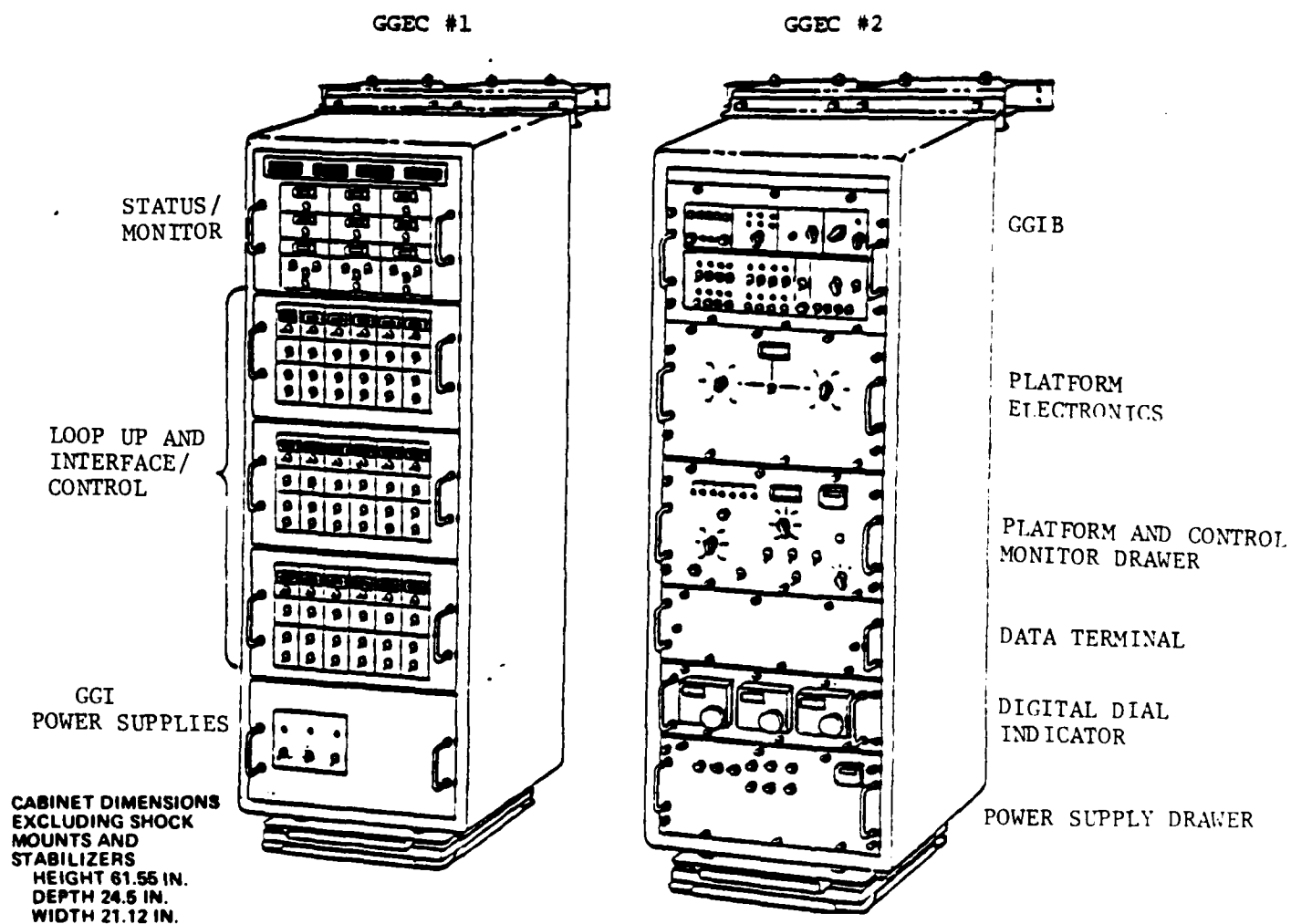


FIGURE 3-15. GRAVITY GRADIOMETER EQUIPMENT CABINETS

A. GGEC #1

Status and Monitor Drawer

Three Loop Control Microprocessor (LCMP) Drawers

Power Supply Drawer

B. GGEC #2

Gravity Gradiometer Instrument Buffer (GGIB) Drawer

Platform Stabilization Electronics Drawer

Platform Control and Monitor Drawer

LCMP Keyboard Terminal

Digital Dial Indicator

Power Supply Drawer

The following paragraphs give a simplified description of each of the major subsystem drawers.

3.3.2 Status and Monitor Drawer (GGEC #1)

The primary functions of the Status and Monitor drawer are to display system status and to control and monitor the operation of the three GGI's and in conjunction with the LCMP drawers (Section 3.3.3) provides the closed loop compensation for the GGI's.

In particular, the Status and Monitor functions are:

- (a) Control of GGI start-up and shutdown
- (b) Provides circuitry for GGI temperature controls
- (c) Provides frequency references for GGI's and Loop Control Microprocessor (LCMP)
- (d) Converts GGI analog outputs to digital
- (e) Provides monitoring meters and lights for gradient outputs and status of loop integrators and demodulators
- (f) Provides safety circuits which remove GGI power based on monitoring GGI power, status of control loops and temperature.

Control and monitoring of each GGI is accomplished independently of the status of the other two GGI's. Discrete switches and displays for the GGI's are mounted on the front panel.

### 1. Displays

System status and GGI operation indicator lights are provided on the front panel, a photograph of which is given in Figure 3-16, as listed in Table 3-1. Separate front panel meters for each GGI display the GGI Block Temperature, Gradient Signal (In Line or Cross), and  $\Sigma$  Amplifier Integrator Output with LED indicators for GGI power on.

### 2. Controls

Each GGI is individually controlled from the front panel through the switches listed in Table 3-2.

### 3. Circuitry

To perform the functions described above, the Status and Monitor drawer contains the following circuitry:

- Reference Signal General - this provides the basic timing for the GGI operation and for data transfer from the LCMP's to the system GGIB. All timing signals from the unit are locked to one 524288 Hz oscillating source. The various frequencies of the output signals are then obtained by dividing down from the oscillator frequency in a series of presettable binary counters. The reference signals generated in this fashion are listed in Table 3-3.

- Bandpass Signal Interface and A/D Converter - this is a tracking A/D converter that takes the analog bandpass signal from the GGI and converts it into a 16-bit parallel digital word for transmission to the LCMP's.

- Compensation Amplifiers - these sum the integrator signals from the LCMP's and the torque drive amplifier signals from the GGI's to form the GGI compensation signals. There are five output signals from the Compensation Amplifiers.

- Temperature Control Electronics - these circuits control the block and case temperature of each GGI. As in other GGI electronics, separate circuits are provided for each GGI. Input signals are obtained from the thermistors on each GGI. Output signals are the GGI block and case heater voltages. In addition, the block temperatures are displayed on front panel meters, the block temperature is sent to the GGI Accelerometer Protection circuitry, and the case temperature is sent to the GGIB.

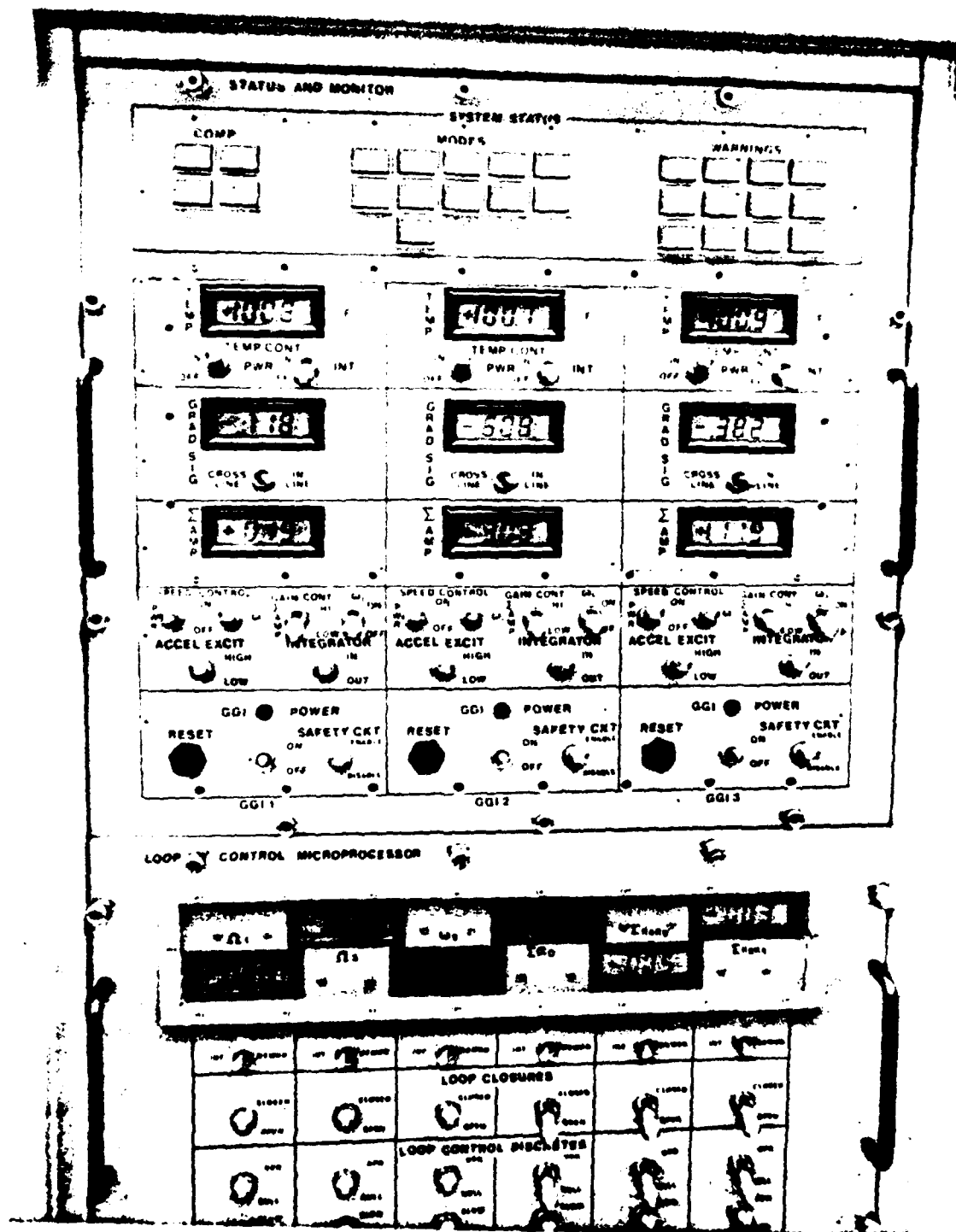


FIGURE 3-16. STATUS & MONITOR DRAWER - FRONT PANEL

TABLE 3-1. SYSTEM STATUS INDICATORS

CDMS Up  
LCMP No. 1 Up  
LCMP No. 2 Up  
LCMP No. 3 Up  
GSS Ready  
GSS Calibrate  
Platform Ready  
Platform Carousel  
Platform Step Carousel  
GGI No. 1 Ready  
GGI No. 1 Initiate  
GGI No. 2 Ready  
GGI No. 2 Initiate  
GGI No. 3 Ready  
GGI No. 3 Initiate  
OBGC Warning  
Platform/Binnacle Warning  
Platform Temperature Warning  
GGI No. 1 Warning  
GGI No. 2 Warning  
GGI No. 3 Warning  
GGI No. 1 Temperature Warning  
GGI No. 2 Temperature Warning  
GGI No. 3 Temperature Warning  
Speed Control No. 1 Ready  
Speed Control No. 2 Ready  
Speed Control No. 3 Ready



TABLE 3-2 GGI CONTROLS

Temperature Control Power On/Off  
 Temperature Control Integrator On/Off  
 Speed Control On/Off  
 Speed Control Power On/Off  
 Speed Control  $\omega_s$  On/Off  
 Axial Shake On/Off  
 Axial Shake  $\omega_a$  On/Off  
 Accel Excit High/Low  
 Integrator In/Out  
 GGI Power On/Off  
 GGI Power Reset  
 GGI Power Safety Circuit Enable/Disable  
 GGI In Line or Cross Gradient Signal Display

TABLE 3-3 REFERENCE SIGNALS

1. GGI Speed Control signals:
  - 4096 pulses/rev
  - 1024 pulses/rev
  - 1 pulse/rev
  - $\omega_s$  at 1.8 Hz
 (where 1 Rev refers to the GGI rotating element)
2. LCMP signals
  - 1 pulse/rev
  - 128 pulses/rev
  - $\phi_s$  10 bits ( $\omega_s$  phase)
  - $\phi_a$  10 bits ( $\omega_a$  phase)
3. Bandpass D/A Converter signals
  - 128 pulses/rev
  - 262144 Hz
4. GGI B Signals
  - 8192 Hz
  - 262144 Hz
5. GGI Axial Shake signal
  - $\omega_a$  at 3.2 Hz

- Accelerometer Protection Circuits - Circuits are provided in the Status and Monitor Drawer to protect the GGI accelerometers from damage. This protection is accomplished by automatically turning off GGI power if a potentially damaging situation should occur.

- Buffer Amplifiers - these are primarily used to interface the analog signals from the LCMP drawers to the Status and Monitor drawer in order to minimize the effects of ground differences between drawers.

- Lamp Drivers - the front panel provides system status, mode and warning indications. The Lamp Driver circuits take the various input signals and perform the required logic functions and power drivers required to illuminate front panel indicators. All indicators are press-to-test types and have two lamps per indicator.

### 3.3.3 Loop Control Microprocessor (LCMP) Drawers (GGEC #1)

The LCMP, a photograph of which is reproduced here as Figure 3-17, processes data from the GGI and returns loop closure signals to it. It also receives signals from the Status and Monitor Drawer. Appendix A discusses the GGI, its output signal processing and loop compensation associated with these instruments. Data that both originate in the GGI and which are eventually sent there, are first processed by the Status and Monitor Drawer. For example, the GGI output signal is analog at the output of the instrument. It then goes through a 14-bit analog to digital converter in the Status and Monitor drawer before going to the LCMP as a digital word. The loop closure analog outputs from the LCMP are buffered in the Status and Monitor Drawer before they go to the GGI.

Other analog outputs used only for metering and recording are also buffered, along with the loop closure signals. Generally, these buffered analog signals are returned to the LCMP where they are displayed by digital meters on the front panel. These meters have built-in analog to digital converters. A photograph of the front panel is given here in Figure 3-18.

Switches on the front panel control which signals are sent to the meters. All meters display either outputs of demodulators or integrators generated by the LCMP's firmware, depending on the operator's selection. The front panel has other switches that null the integrators or select the rate at which loop closure corrections are made.

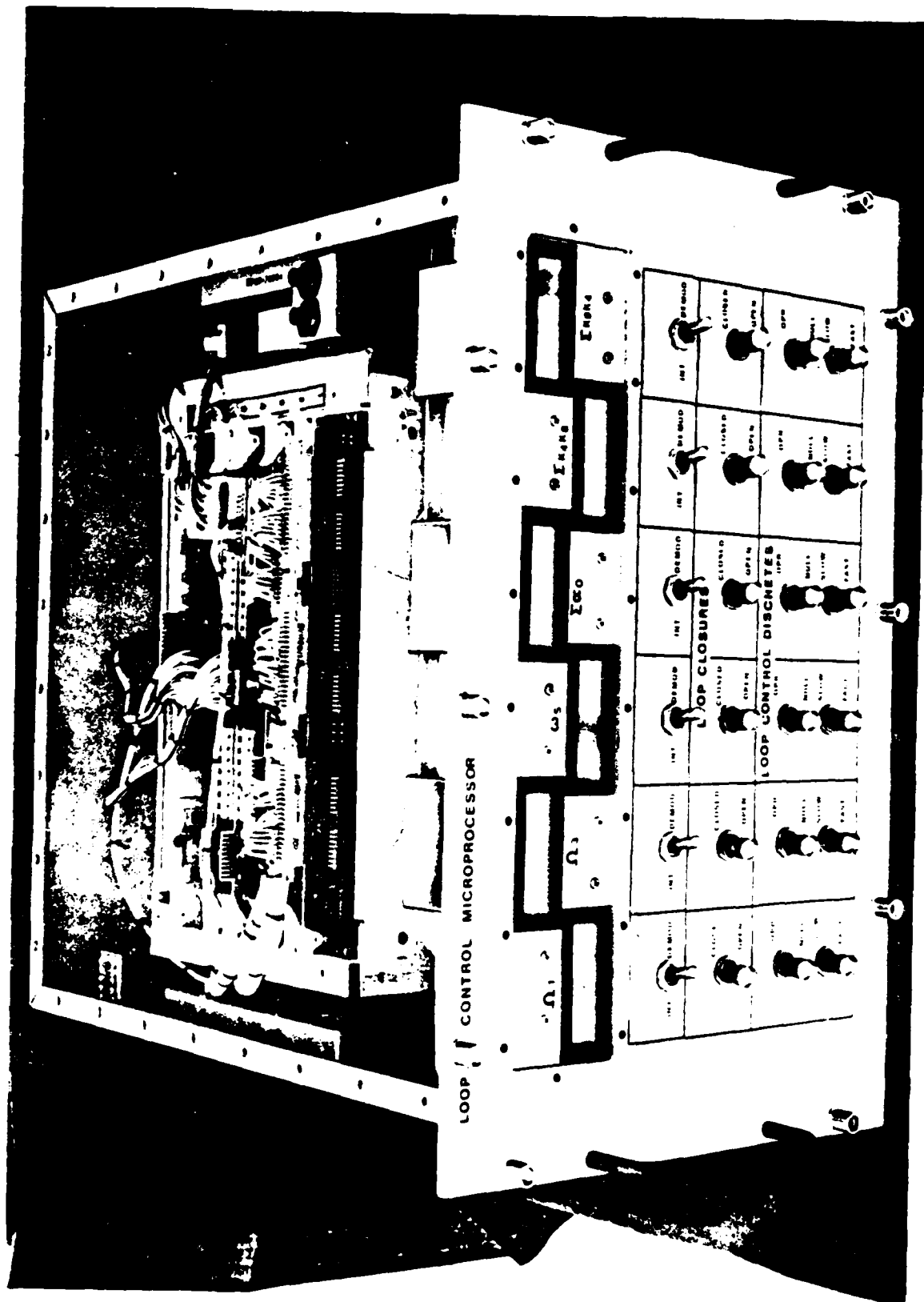


FIGURE 3-17. LOOP CONTROL MICROPROCESSOR (LCMP) DRAWER

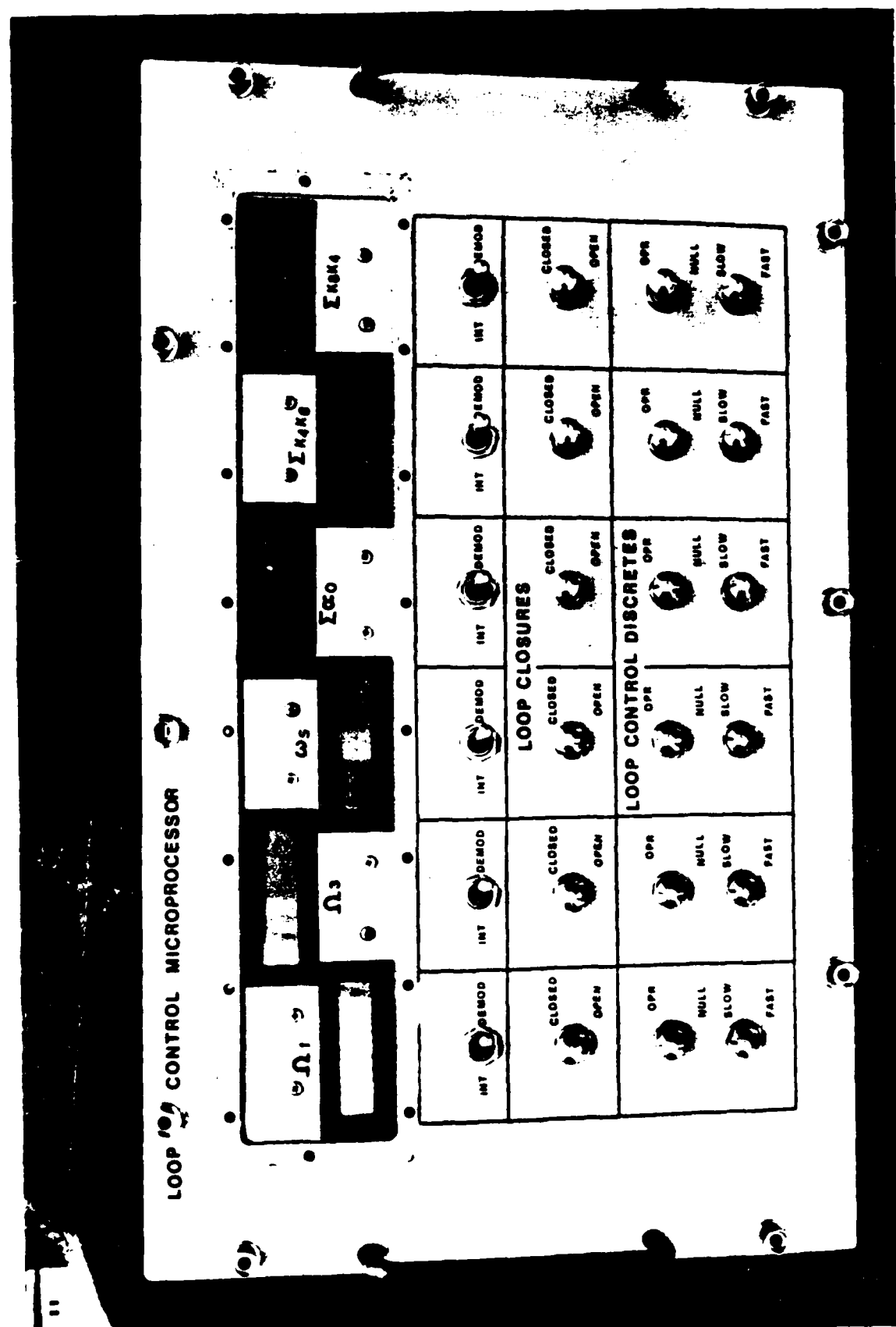


FIGURE 3-18. LOOP CONTROL MICROPROCESSOR (LCMP) DRAWER - FRONT PANEL

Data is also sent from the LCMP to the DVOC under control of the GGIB. These data are transferred in a 12 word series of 16 parallel bits every two seconds.

The heart of the LCMP is the microprocessor itself, a Texas Instrument 9900 series. This microprocessor is programmed to perform the functions described in Appendix A. The main components of the firmware are demodulation of the summed acceleration signal from the GGI, subsequent filtering and integration of the demodulated signal to form the required scale factor compensation command as described in Appendix A. The gravity gradient signals are extracted by demodulating at twice the wheel rate and by filtering through the Butterworth filters. The resulting in-line and cross-gradient signals are then routed to the Dedicated VAX-11 Operational Computer (DVOC).

The keyboard/printer/terminal, located in GGEC #2, programs the LCMP's. The front panel is illustrated in its closed position in Figure 3-19 and in its operating condition in Figure 3-20 through the keyboard, the operator can call up the firmware already in place in the LCMP and insert certain parameters unique to each GGI. Since only one keyboard is used, the operator must select which LCMP he wants to address with the switch adjacent to the keyboard (see Figure 3-20).

The LCMP responds to three interrupts, two from the system and one from the GGIB. The controlling interrupt occurs 32 times per second. After detecting this interrupt, the LCMP reads the GGI output data. It also accepts integrator control switch discrettes and discrettes from other parts of the system such as the status of the rotor speed control and carouseling. The LCMP computes loop closure and display data, and using built-in digital to analog converters, generates the outputs that go to the Status and Monitor drawer for buffering.

A 4 second interrupt is used as the system time reference. It clears a software counter in the LCMP which thereafter counts the controlling (32 Hz) interrupt. This count is sent to the DVOC as part of the LCMP message where it is used to monitor the performance of the system.

A third interrupt comes from the GGIB to prepare for a data transfer. Twelve, 16-bit words constitute the LCMP message. The more significant 8-bit byte contains the address of the data which is contained in the less significant byte. When the GGIB detects the changing bit pattern of the address, it passes the word to the DVOC.

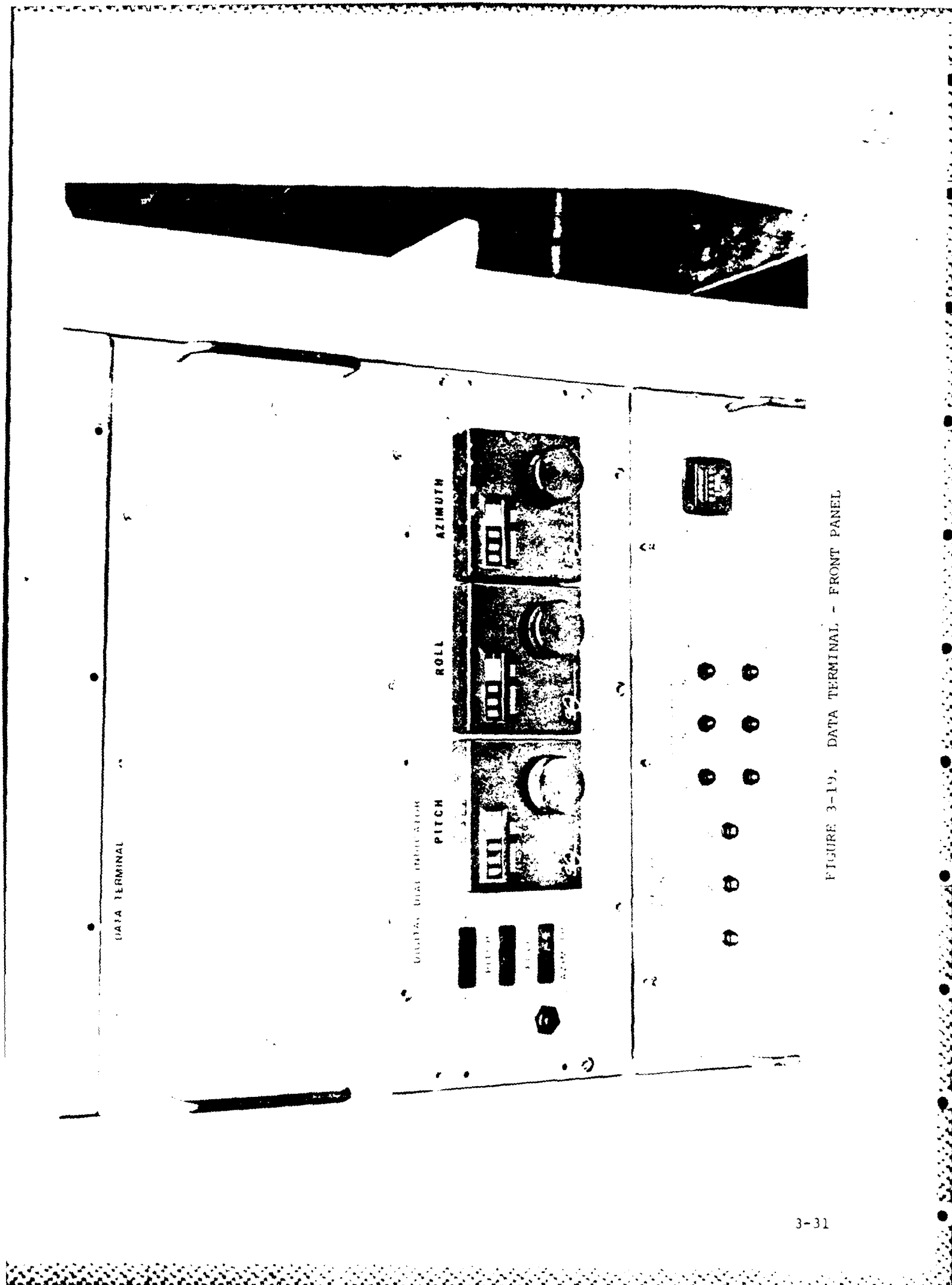


FIGURE 3-19. DATA TERMINAL - FRONT PANEL

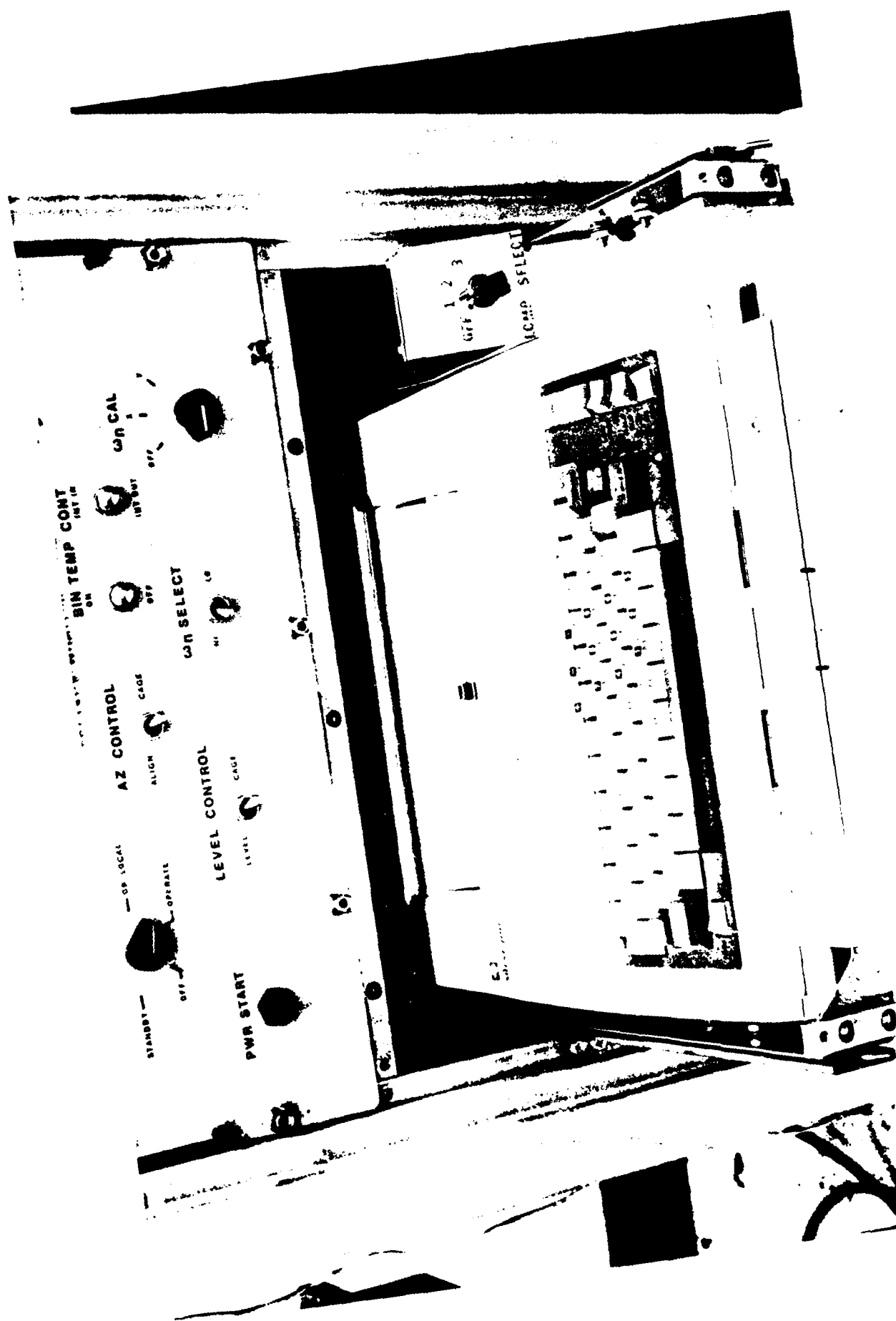


FIGURE 3-20. LAMP DATA TERMINAL

#### 3.3.4 Gravity Gradiometer Instrument Buffer (GGIB) Drawer (GGEC #2)

The GGIB is essentially a buffer which processes, organizes and transfers data between the Dedicated VAX-11 Operational Computer (DVOC) and the rest of the GSS. It also established the times when these transfers occur. The DVOC, LCMP's and system, all transfer data during specific time intervals determined by the GGIB.

Data are split into six messages. Three messages consist of digital data transferred from each of the three LCMP's to the DVOC. Each LCMP message has data words and checksum words generated serially in the LCMP. The LCMP makes the data available in a 16-bit parallel format, and generates 12 words serially to compose a message.

Data acquired from various parts of the system are organized into words by the GGIB to form two messages for the DVOC. These messages originate in the GGIB and are designated message GGIB<sub>1</sub> and message GGIB<sub>2</sub>.

Signal processing is required to get these data into 16-bit words that the DVOC can accept. Platform acceleration comes to the GGIB as series of pulses whose repetition rates are proportional to acceleration. Velocity accumulators detect these pulses and integrate them to develop 16-bit velocity words. The DVOC later takes differences between corresponding velocities transferred in different messages and restores acceleration by dividing this difference by time. Platform position data is received in synchro format. Synchro to digital converters in the GGIB process these signals into 16-bit parallel data. Discrete data from the system are also organized into words by the GGIB. Finally, the GGIB contains a clock whose digital output identifies the time when the message is transferred.

A photograph of the GGIB drawer is reproduced here as Figure 3-21 and a photograph of the back plane wiring employed is shown as Figure 3-22.

All words in the GGIB<sub>2</sub> message are processed in the GGIB's 12-bit analog to digital converter. Some words give environmental conditions like temperature, pressure and relative humidity while others are jitter signals obtained from the jitter electronics. The last A/D converter word is generated from a test signal that aids in calibrating the converter and verifying its performance.



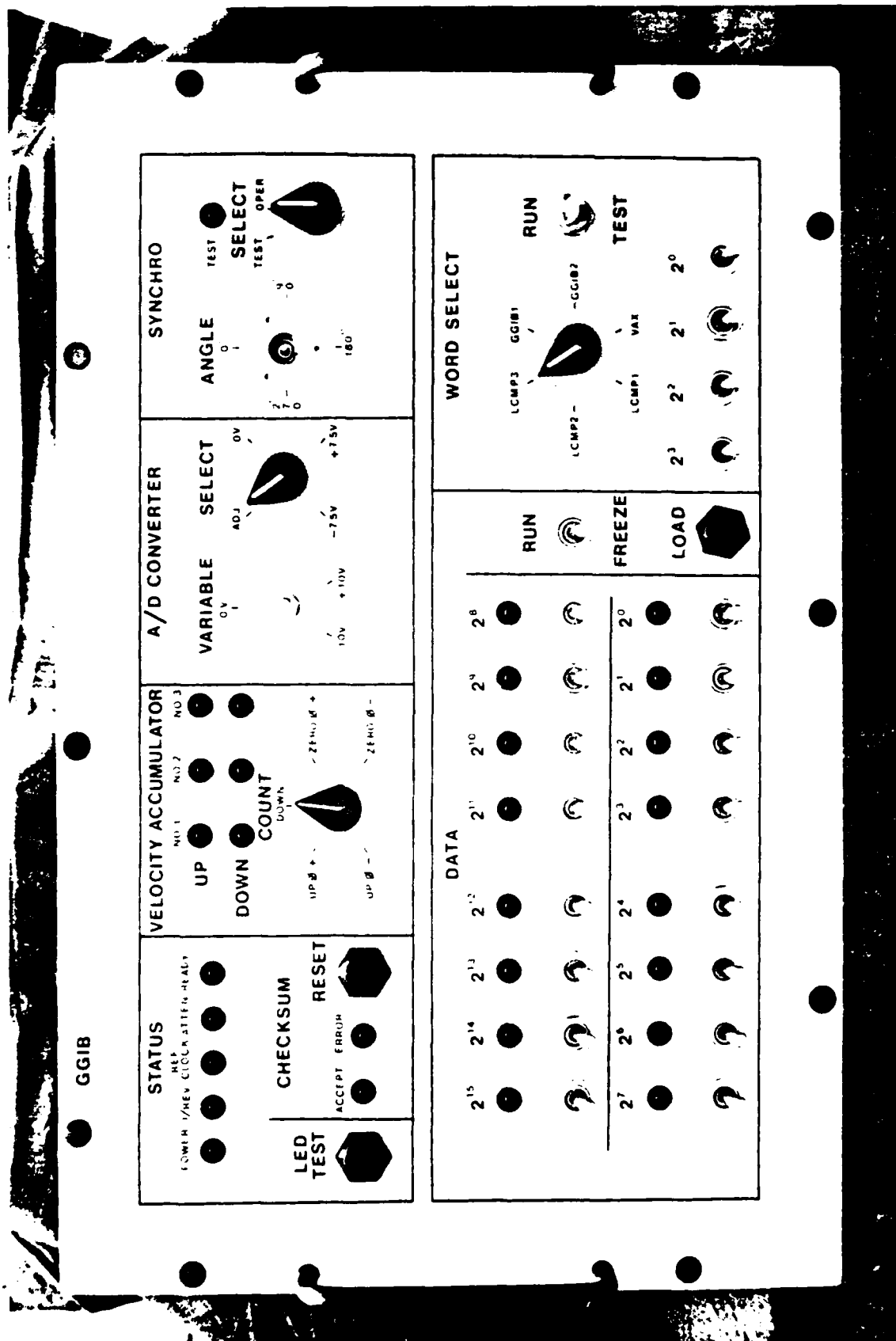


FIGURE 3-21. GGIB DRAWER - FRONT PANEL

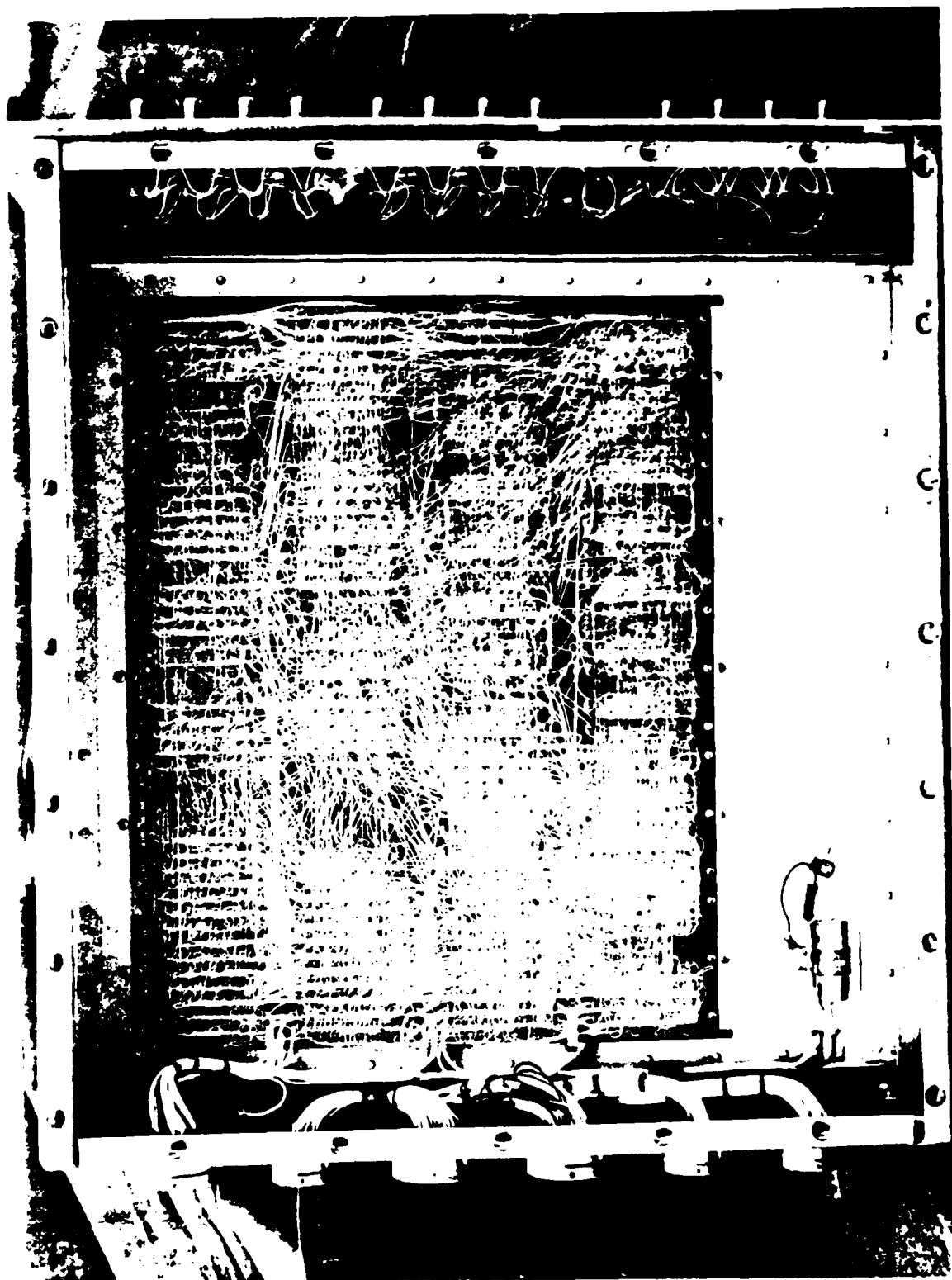


FIGURE 3-22. CUB - BACK PLANE WIRING

Both the GGIB<sub>1</sub> and GGIB<sub>2</sub> messages include a checksum word. This word is the modulo 16 sum of all the other words in the message. Messages with checksum errors are rejected by the DVOC.

A single message is sent from the DVOC to the system and is designated the VAX message. It contains discrete words, gyro torquing words and strip chart recorder words. Torquing and recorder data are transformed into analog outputs by 12-bit digital to analog converters in the GGIB. Discrete data are latched and made available to the system. The DVOC sends a checksum word to the GGIB similar in content to the ones sent in the reverse direction. If the GGIB computes a checksum differing from the one received from the DVOC, the GGIB discards the entire VAX message in which the error was found.

### 3.3.5 Platform Control and Monitor

The Platform Control and Monitor drawer contains a sequence controller that provides control signals to the Platform Electronics drawer as shown in Figure 3-23. Front panel switches provide individual control of the platform servo loops. The sequencer provides six basic states: Off, Standby, Gyro Start, Gyro Cage, OP Local, and OP Remote. These states are activated in this order, up to the state indicated by the sequence control switch on the front panel.

In the Off state, all power is removed from the Platform Electronics. In Standby, the +28V power supply is activated. In Gyro Start, the gyro spin motor is energized. Initially, the motor is over excited to insure gyro wheel run up. After a time delay of approximately 80 seconds, the excitation is reduced to the normal operating level. In Gyro Cage, power is applied to the gyro constraint electronics. The gyro operates in the rate constrained mode where each pick-off output is fed through appropriate networks and amplifiers to drive the torquer to null the pick-off signal. This torquer drive voltage is proportional to the gyro case rate. The platform Slip Ring Servo is also activated. This is an auxiliary servo which drives the azimuth slip ring cartridge to remove the major source of friction seen by the azimuth gimbal so that fine, jitter free, platform operation is possible.

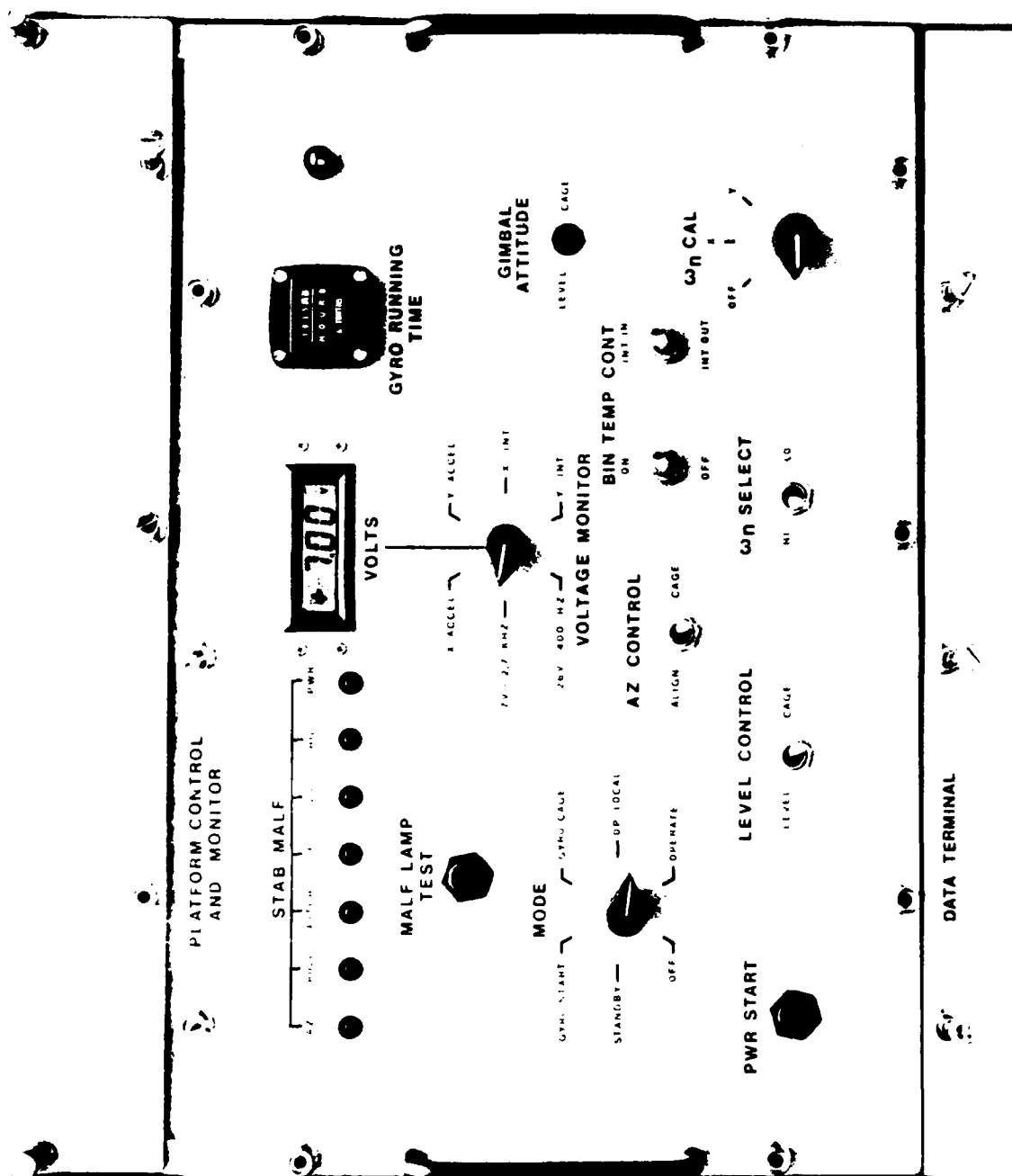


FIGURE 3-23. PLATFORM CONTROL & MONITOR DRAWER - FRONT PANEL

After a 15 second delay, to enable the gyro constraintment electronics to settle, the OP Local state can be activated. In this state, the gyro rate signals are sent to the Platform Electronics Drawer to stabilize the platform. Operator control of platform position is now available from the switches and knobs on the front panel of the Control and Monitor Drawer.

In OP Remote, the platform position is controlled from the DVOC through the GGIB. The principal operations of the GSS are performed in this mode. The Gravity Sensor Platform is Schuler loop leveled and aligned and the GSP accelerometers integrated to produce velocity. The SINS velocity outputs are compared with the GSS velocity outputs and control correction made. These corrections are estimated by a Kalman filter. All computations are performed in the DVOC. Appendix B discusses the computer program.

GGEC #2 also contains safety and monitoring circuits. The Stab Safety Circuit detects excessive platform rates. When detected, the sequencer returns to the Gyro Start state. The Gyro Speed Monitor detects changes of gyro rotor speed from its synchronous value. When detected, the sequencer returns to the Gyro Start state. The sequence control switch must be momentarily returned to standby position before resuming sequencing. When the slip ring servo motor draws excessive current, the Slip Ring Servo Control disables the servo and the sequencer returns to the Gyro Start position. If an excessive deviation of any of the power supply circuits is detected by the Power Safety Circuit, the sequencer returns the system to the OFF state. Momentary depressing the Power Start button restores normal sequencing if the condition has been rectified.

To prevent gimbal lock when the roll (middle) gimbal angle exceeds  $45^{\circ}$ , the sequencer is placed in the OP Local state and the pitch/azimuth axes are disabled.

To eliminate undesirable transients, particularly those resulting from initial conditions on the integrators in the stabilization loop, the system is put into the Gyro Caged state when toggling the switch which selects between Level (accelerometer control) and Caged (platform synchro control) operations. The Gyro Caged state is also selected when transferring control from Local to DVOC.

Figure 3-24 summarizes the Control and Monitor Drawer functions.

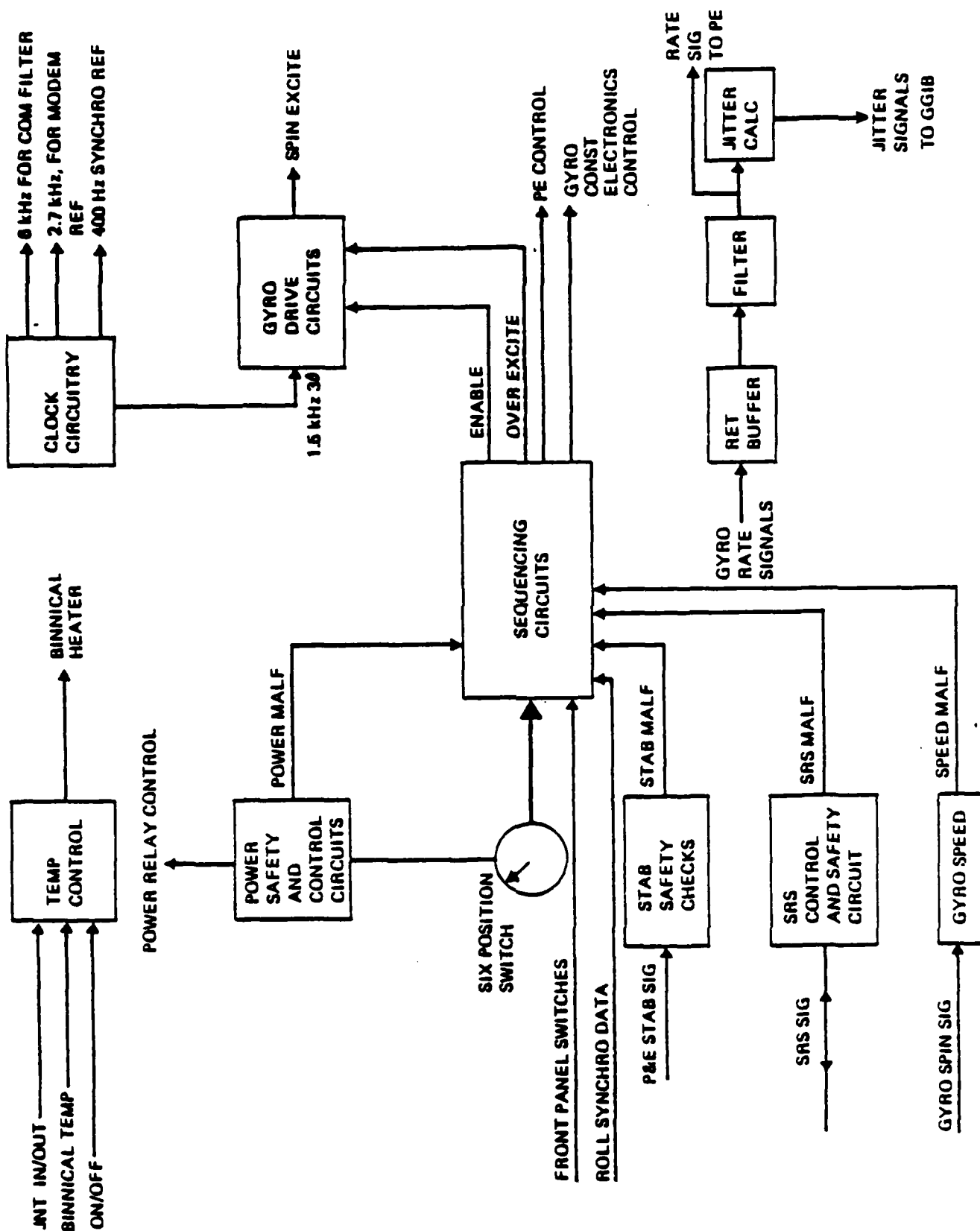


FIGURE 3-24. CONTROL AND MONITOR DRAWER FUNCTIONS

### 3.3.6 Platform Electronics Drawer

#### 3.3.6.1 General

The function of the Platform Electronics System is to position and maintain the platform at a desired attitude. The desired attitude is determined by specific operational, calibration or test requirements. The position commands may be selected locally from the GGEC #2 console or remotely from the DVOC computer (see Appendix B). The handoff is made by the MODE selector switch on the Platform Control and Monitor panel on the GGEC #2 console, a photograph of which is reproduced below as Figure 3-25.

The basic position modes are:

- GGEC No. 2 Control

1. Level Axes (Pitch/Roll)

- a. Cage - The platform Pitch and Roll axes are positioned to angles commanded by nominal settings from the GGEC #2. The gimbal angles are precisely measured by 1X and 36X synchros, but only the 1X synchro is used during GGEC #2 control.

- b. Level - The platform Pitch and Roll axes are driven so that the platform's inner element is leveled (azimuth axis aligned with local vertical). The level plane is defined by an orthogonal accelerometer pair on the inner element.

2. Azimuth Axis

- a. Cage - The azimuth axis is positioned to an angle commanded by a manual setting from the GGEC #2. The azimuth gimbal angle is measured by 1X and 36X synchros, but only the 1X synchro is used during GGEC #2 control.

- b. Align - The azimuth axis is positioned by gyro-compassing; i.e., the platform X-axis seeks North by nulling the earth's rate measured by the East gyro. This is not a precision alignment and, as currently configured, the operating modes use azimuth to SINS slaving.

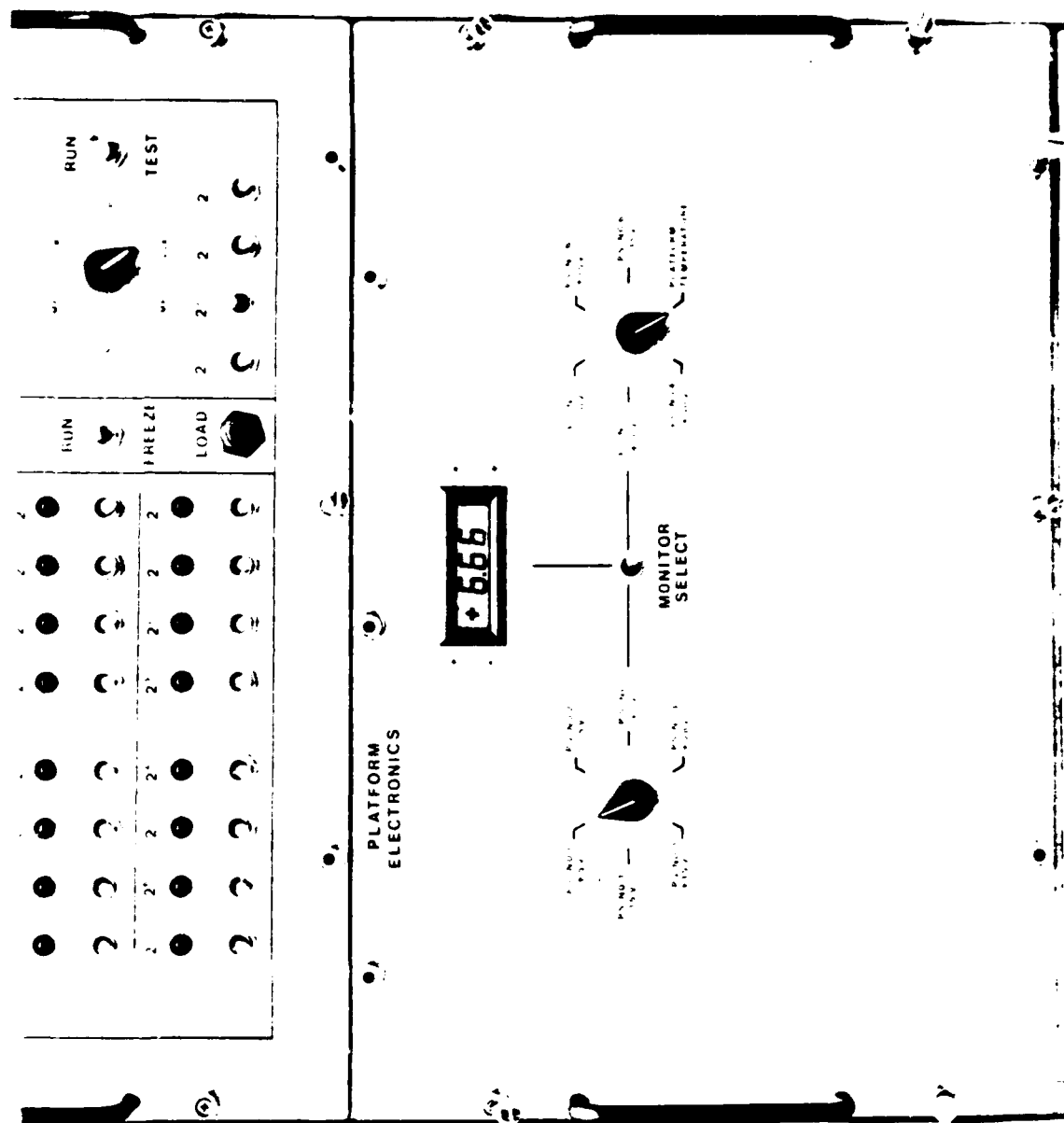


FIGURE 3-25. PLATFORM ELECTRONICS DRAWER - FRONT PANEL



- DVOC Control

1. Cage - The platform gimbals are driven to their synchro nulls. The gyro torquing commands for each axis are generated by computer algorithms from the indicated error of the sampled synchros.

2. Slave - Two options exist in this mode. In the first, the three platform angles are driven to computer commanded angles inserted by the operator from the computer terminal. The gimbal angle indicators are the 1X and 36X synchros.

In the second option, the commanded angles are the gimbal angles of the INS System.

3. Run - The azimuth synchro is slaved to the SINS azimuth. Level control is established by solving the navigation equations with velocity updates from the INS.

#### 3.3.6.2 Azimuth System

Figure 3-19 depicts the Azimuth Platform Stabilization System.

The Azimuth and Level gyros are of the dry, tuned suspension type. These gyros are operated in the rate constrained mode. The closed constraint loop frequency response has a  $90^\circ$  phase lag at 85 Hz.

The gyro measured azimuth rate error,  $\psi_{PM}$ , is the primary stabilization signal which is fed to the Stabilization Electronics. The electronics provides the compensation networks and gains to provide a closed loop response (defined by frequency at  $90^\circ$  phase lag) of 33 Hz in azimuth.

The output of the Stabilization Electronics goes to the Torquer Commutating Electronics. Since the torquer is of the brushless type, distribution of excitation between its sine and cosine windings (the commutation function) is determined by the rotor position with respect to the stator. This position is inputted to the commutating electronics by a one-speed (1X) synchro on the azimuth gimbal shaft. The outputs of the 1X synchro and a 36X synchro for precision, are fed to a synchro to digital converter and the angles sent via the buffer electronics to the DVOC computer.

The platform position is commanded by differencing a torquing command rate with the gyro measured rate. The difference signal precesses the gyro via the gyro torquer.  $\psi_{PM}$  is driven to zero by the stabilization system at which time the gyro case rate, hence, the platform rate is the same as the commanded rate.

The command rates are generated in each mode as outlined above in Section 3.3.5. With the GGEC selector switch in OPERATE, the DVOC generates the commands. With the selector switch in the OP Local mode, the command is generated by analog electronics.

As shown in Figure 2-26, two local options exist. In Cage, the command is the error signal generated by the difference between the LX synchro output and the manually selected position. The difference signal is generated by a differential synchro (DG) whose shaft is set by the manual position control.

In the align mode, the compensated output of the vertical gyro which measures the "east" component of earth's rate is used as the command signal. In this mode, the platform is slewed in azimuth to null the "east" gyro earth's rate measurement.

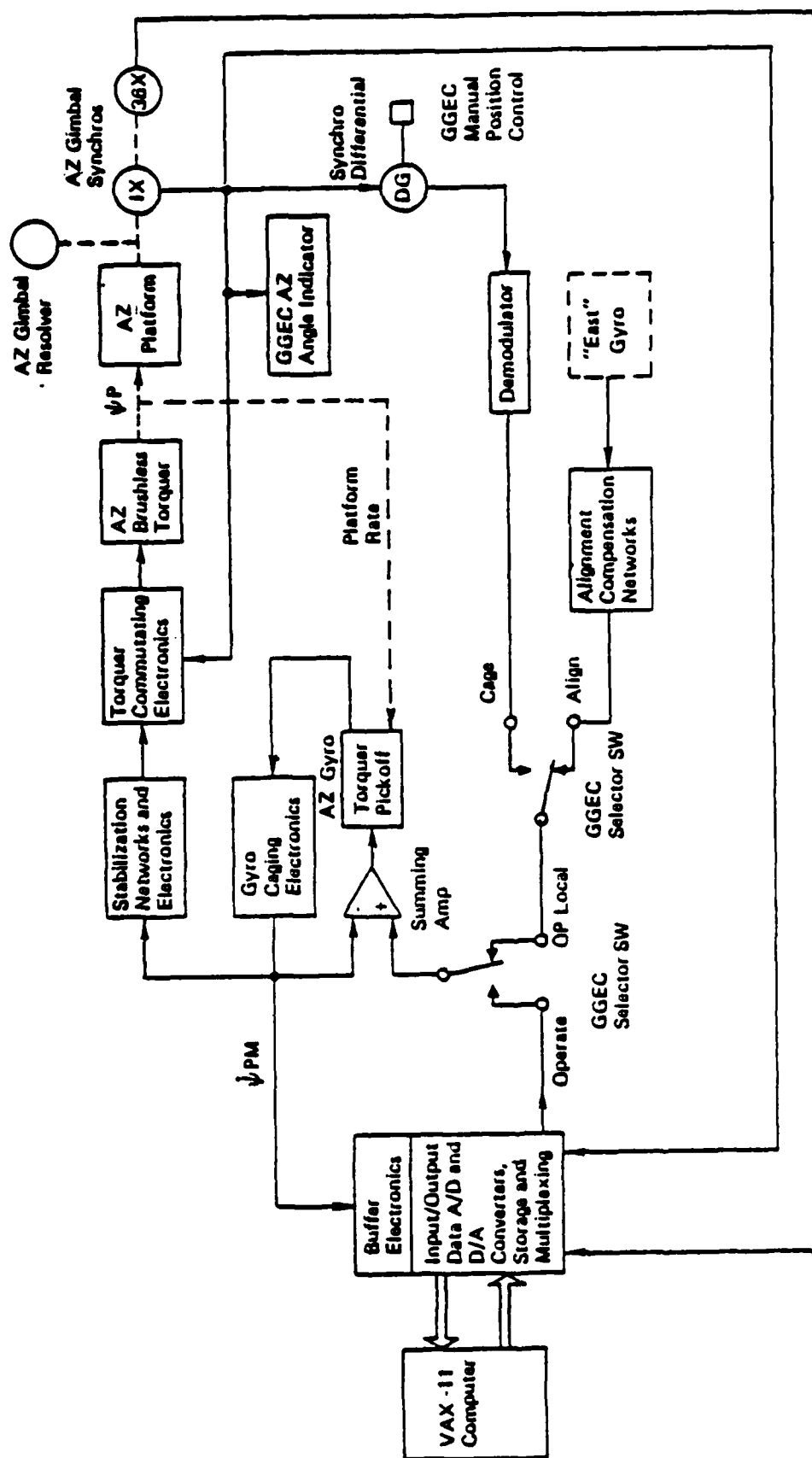
#### 3.3.6.2 Pitch/Roll Stabilization System

Figure 3-27 depicts the pitch and roll gimbal axes control of the platform.

The basic operation of the pitch and roll axes control systems are as described in the preceding section on azimuth stabilization. The pitch and roll stabilization loops have closed loop frequency responses of 17 Hz and 23 Hz, respectively, with response being defined as the frequency at  $90^\circ$  phase lag.

The essential similarities between the three loops are:

- Level and azimuth gyros have the same constraintment electronics,
- Pitch, roll, azimuth stabilization networks have the same morphology with gain and compensation network variations to account for the different gimbal inertias and resonances,
- Torquer commutating electronics and brushless torquers are the same design for the three axes,
- All attitude controls are effected through torquing the appropriate gyros except for the cage mode in local operation. This difference is discussed further below.



$\psi_P$  AZ Gimbal Angle  
 $\psi_{PM}$  Gyro Measured AZ Rate

FIGURE 3-26. AZIMUTH PLAT STAB SYSTEM



Features unique to the Pitch/Roll systems are:

- The level gyro X,Y axes and the pitch, roll gimbal axes are misaligned by the platform's azimuth angle,  $\psi_p$ . Hence, the two gyro measured rates,  $\dot{\phi}_x$  and  $\dot{\phi}_y$ , do not each directly control a gimbal torquer as does the azimuth gyro. The two rates are resolved through the azimuth resolver to obtain the components of the platform rates along each torquer axis. The resolved rates are the error signals processed by the stabilization systems to drive the torquer along that axis.
- The gimbal synchros measure the angle about the torquer axes. Hence, when in the OP Local mode with the Cage option selected, the LX synchro error signal is used to position the torquer on the same axis. In this mode, the level gyro rate outputs resolved into the gimbal coordinator, function as angle rate dampers.
- In OP Local with the Level option selected, the X,Y accelerometers torque the gyros directly since the gyro axes and accelerometer axes are aligned together for any platform heading the instruments both being mounted to the platform's inner element.

### 3.4 The Dedicated VAX-11/780 Operational Computer (DVOC)

#### 3.4.1 Hardware

The Dedicated VAX-11/780 Operational Computer used with the GSS ADM equipment is a government furnished Digital Equipment Corporation VAX-11/780 digital computer suitably modified to accommodate the anticipated NTV environment (vibration, etc.). The basic complement of equipment, shown in its unmodified form in Figure 3-28, consists of:

- The CPU (Central Processing Unit)
- Mass bus Adaptor
- Two Magnetic Tape Units
- Two Magnetic Disc Drives
- One High Speed Line Printer
- One Computer Terminal/Printer

Figure 3-29 is a photograph of two unmodified VAX-11/780 used for software development.

One of these VAX-11/780 computers was modified before delivery to the NTV to ensure that it would remain operationally reliable under the anticipated environment (i.e., vibration, ship's motion etc.) of the NTV. Figure 3-30 illustrates

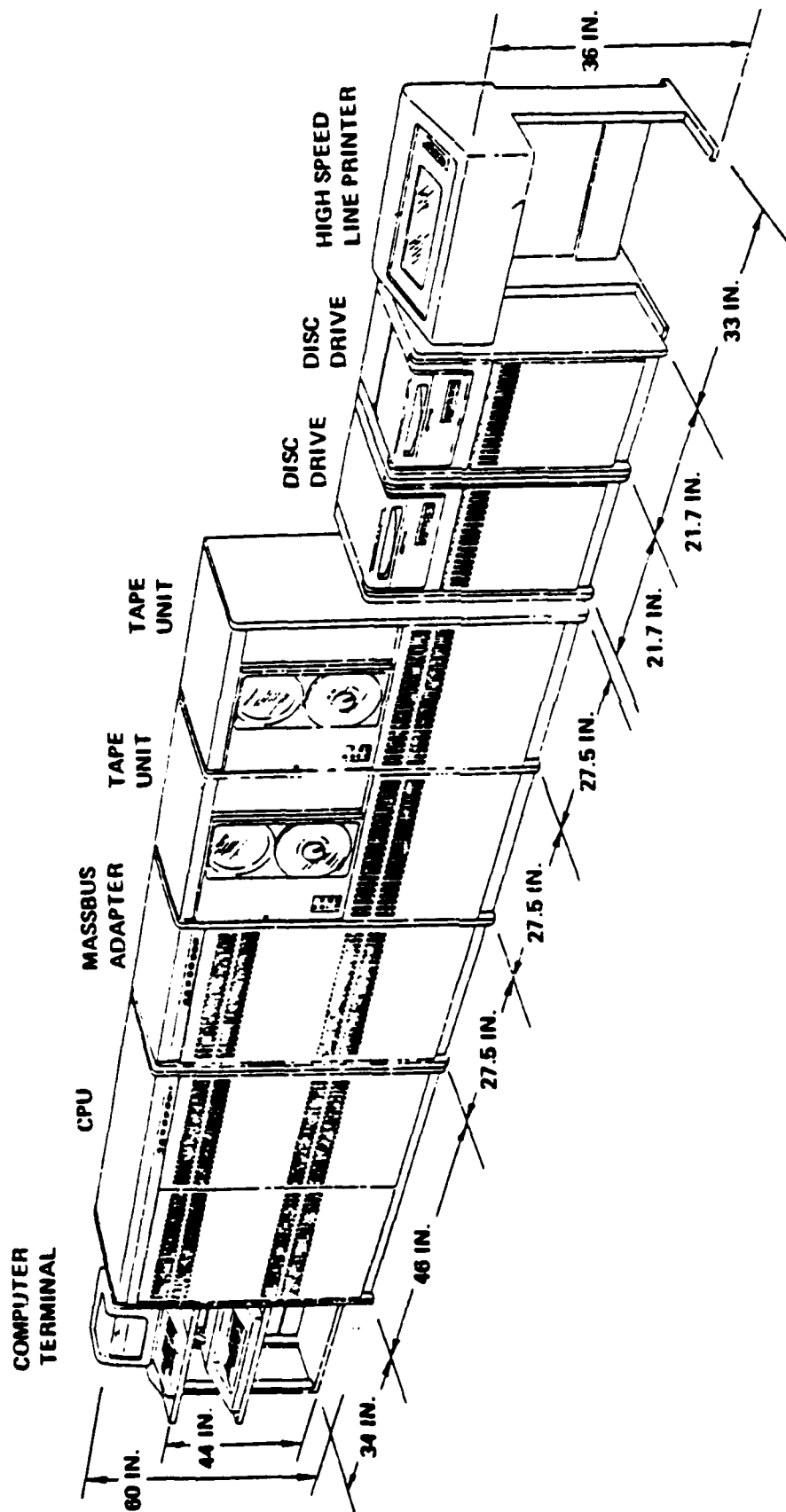


Figure 3-28. GSS Operational Computer Facility



FIGURE 3-29. TWO VAX-11/780 COMPUTERS USED FOR SOFTWARE DEVELOPMENT

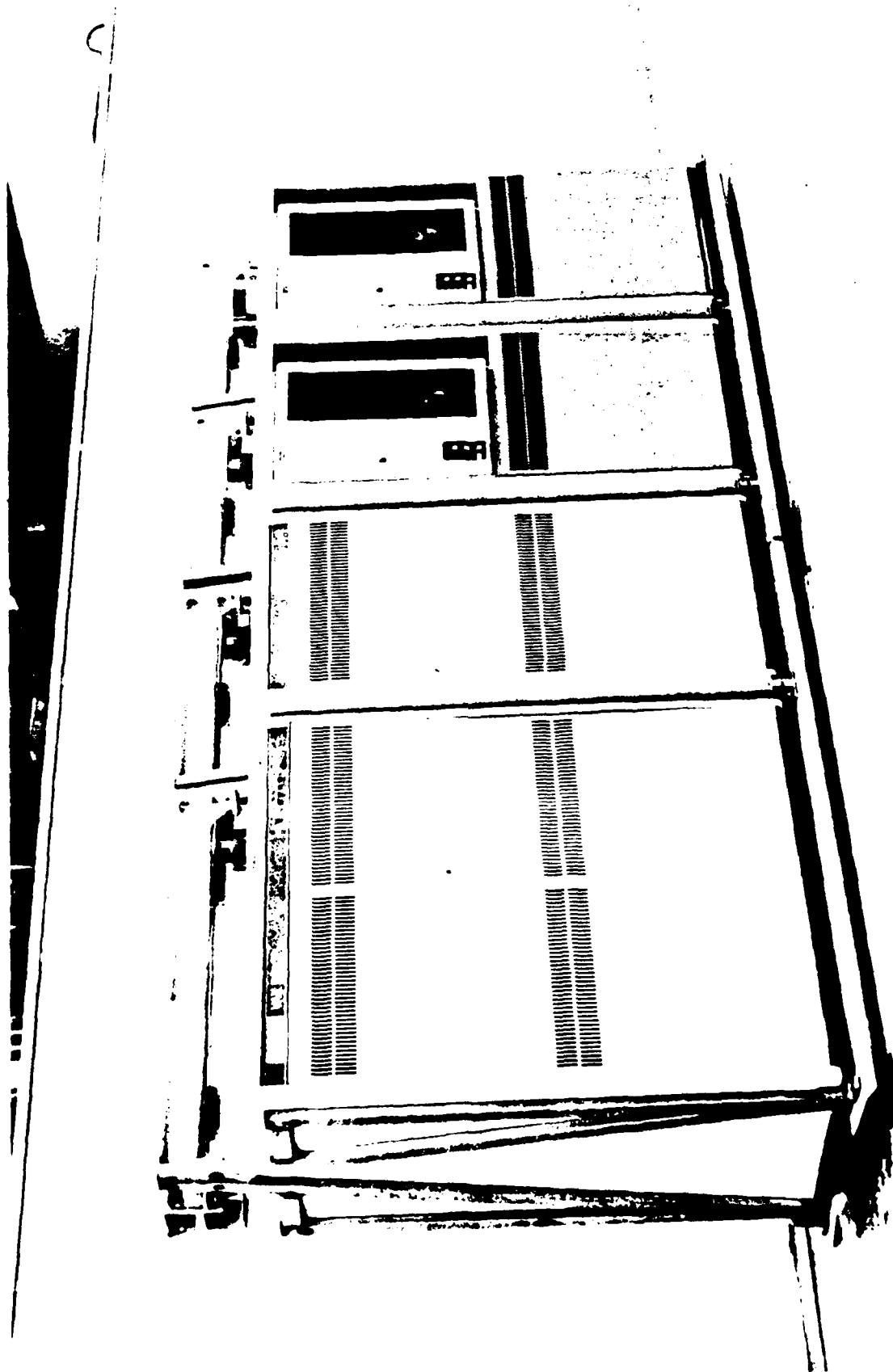


FIGURE 3-30. MODIFIED VAX-11/780 CABINETS



the modifications of the four main cabinets - the CPU, the Mass bus Adaptor, and two tape drives. The modification to the high speed line printer and the computer terminal may be seen in Figures 3-31, 3-32, and 3-33. Figure 3-34 shows the disc drive before and after modification. The disc drive received more attention than the other cabinets because of the requirement that the disc remain approximately horizontal regardless of the instantaneous ship motion. This was achieved by gimballing the disc drive in the roll axis of the ship. Pitch motion was found to be non-critical.

#### 3.4.2 Software

The software resident in the DVOC enables the computer to perform the following basic functions of the ADM GSS (a more detailed discussion of the required computer programs and system equations are given in Appendix B):

1. Gravity Gradient Tensor Solution in NED Coordinate System

- Gimbals + Ship's Self Gradient Computation and Compensation
- Pre-mission Exponential Computation and Compensation
- Alignment and Scale Factor Compensation
- LaPlace and Least Square Solution
- Transformation and Transposition of Elements of Gravity Gradient Tensor into NED Coordinates
- Data Pre-Processing

2. Inertial Instrument Calibration, Computation and Compensation

- Gyro Misalignments and Scale Factors
- Accelerometer Misalignment and Scale Factors
- GGI Misalignments and Scale Factors

3. Alignment to and Leveling to SINS Coordinates

- Azimuth Gimbal Error Computation between SINS and GSS
- Velocity (N,E) Error Computation between SINS and GSS
- Derivation of Dynamically Accurate Leveling Equations
- Computation of Azimuth Gimbal Matching Transfer Function
- Computations and Commands for NED, Constant Carouseling and Step Carouseling Modes

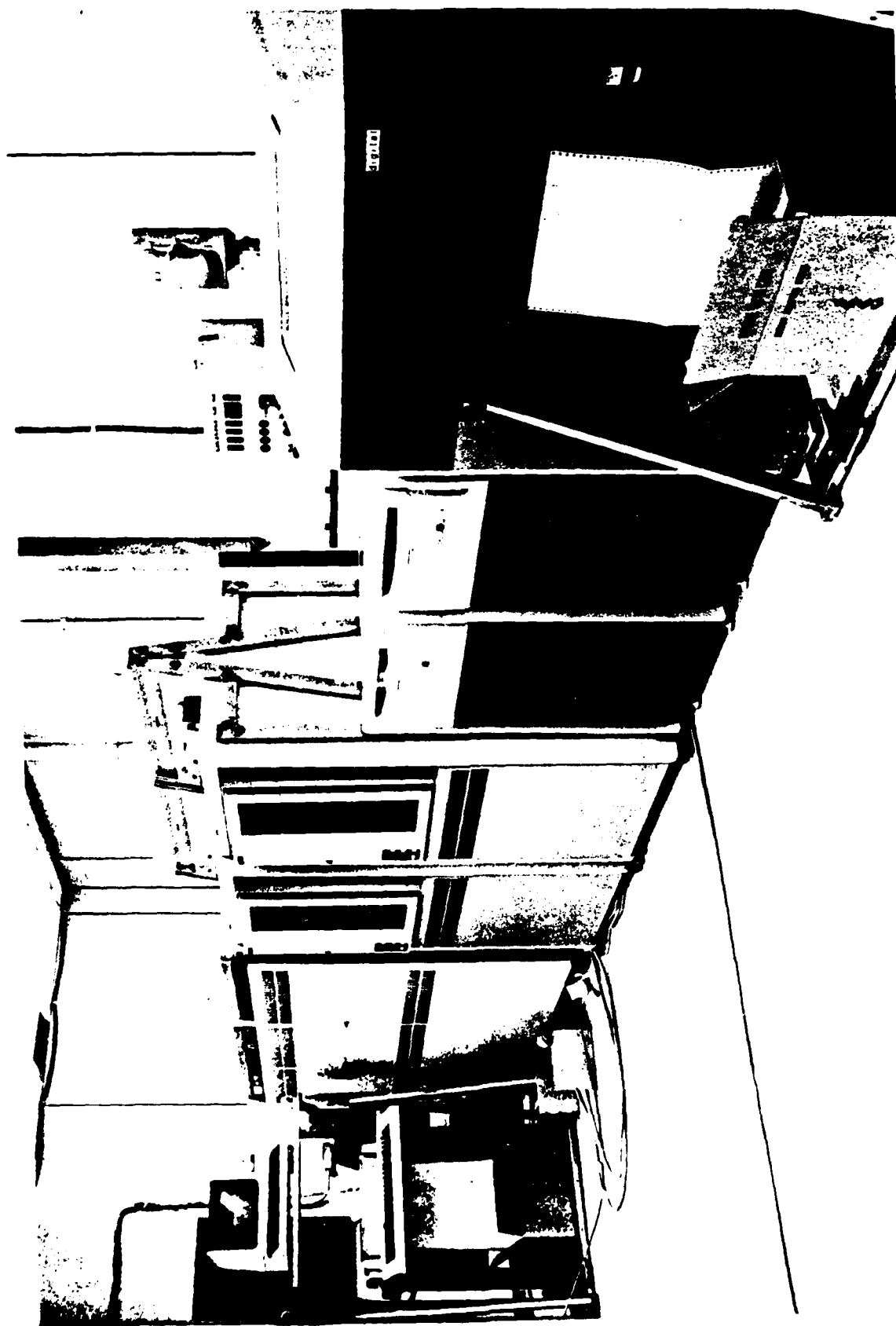


FIGURE 3-31. PARTIALLY MODIFIED VAX-11/780

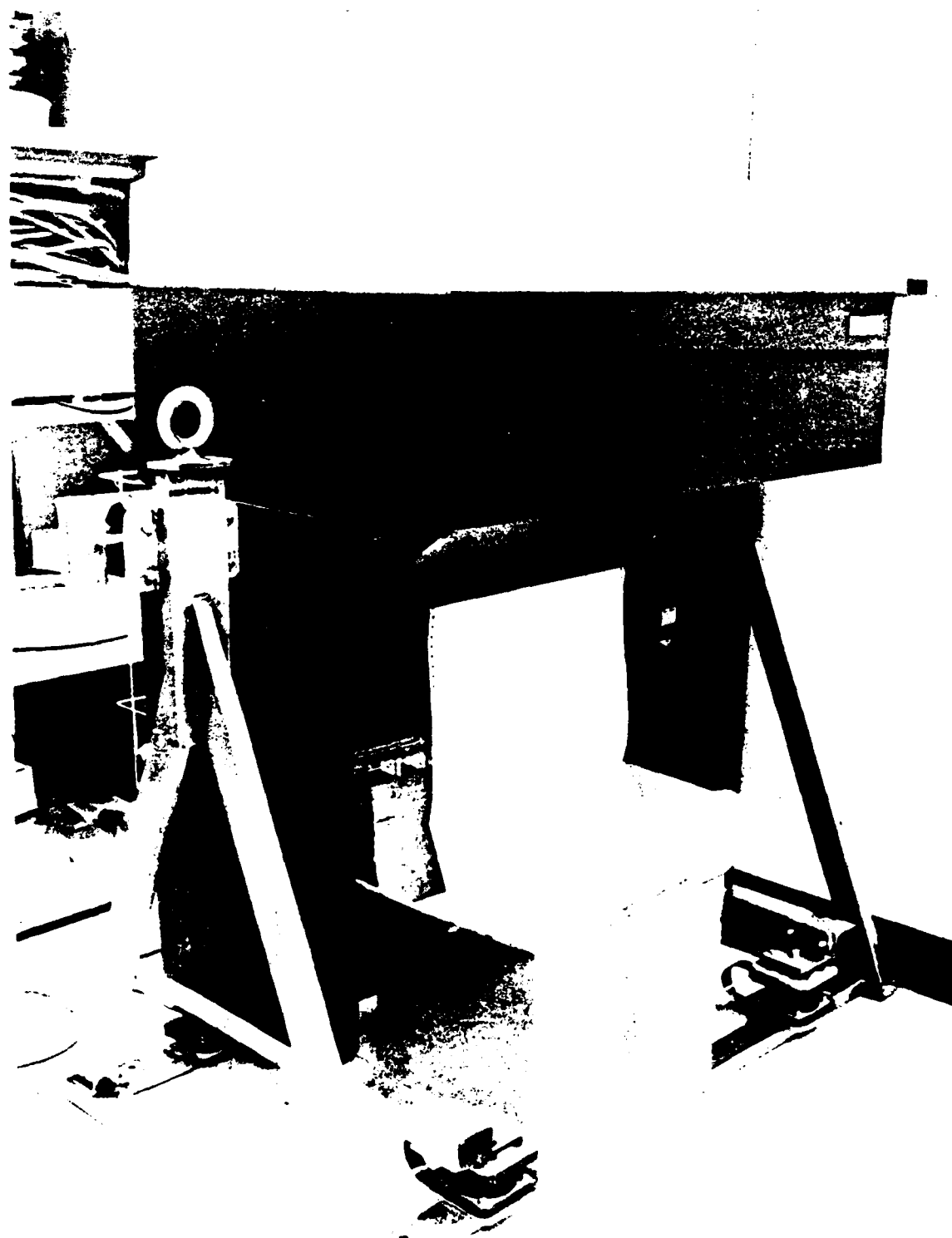


FIGURE 3-32. MODIFIED HIGH SPEED LINE PRINTER

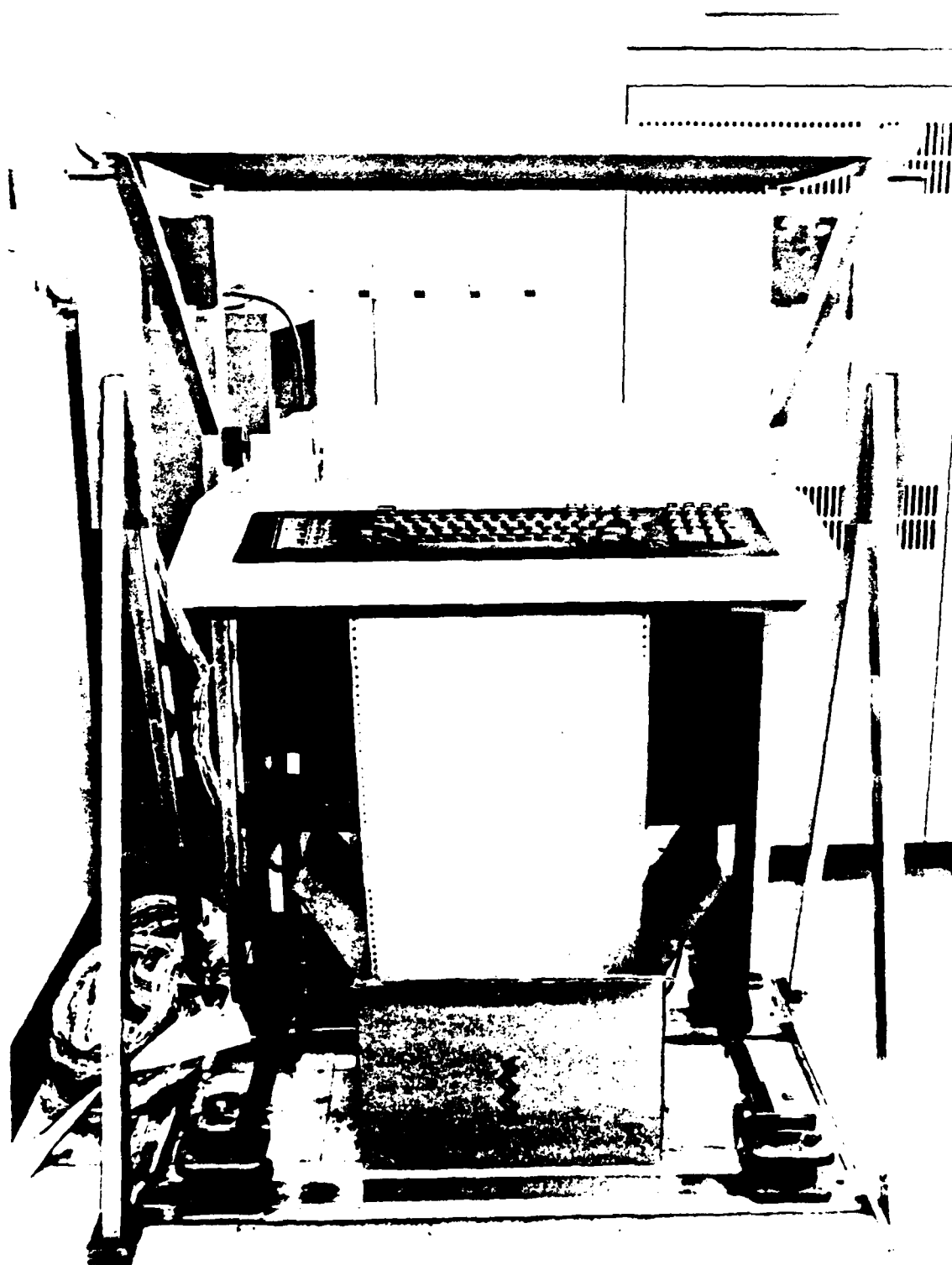


FIGURE 3-33. MODIFIED COMPUTER (DECwriter)



FIGURE 3-34. DISC DRIVE BEFORE & AFTER MODIFICATION

#### 4. Data Analysis

- Compute Means, Trend and Standard Deviations of Selected Signals over Command Record Length
- Compute Power Spectral Densities of Selected Signals over Commanded Record Length.

#### 5. Data Recording

- Log Data or Selected Signals for further Analysis at SSM and Bell.

In order to provide these functions, twenty software functions were designed and programmed. These functions are characterized in the following groups:

##### Calibration Functions

Accelerometer Calibration  
Gyro Calibration  
GGI Scale Factor Calibration  
Prepermission Calibration

##### GGI Processing Functions

Gimbal Self Gradients  
GGI Compensation  
Gradient to Tensor Processing  
Tensor Rotation and Decarouseling  
Performance Monitor

##### GSP Control Functions

Diagnostics  
Status and Control  
Accelerometer Compensation and Resolution  
Carousel and Attitude Command  
Platform Control  
Resolution and Gyro Compensation

##### System Control Functions

Start-up and Operator Control  
Program Control (Control Process)  
Input/Output Control  
Peripheral I/O  
System Affiliated

These software functions are interrelated as shown in the block diagram of Figure 3-35 and, as mentioned above, are more fully described in Appendix B.

### 3.5 Platform Enclosure (Binnacle) and Cooling System

The Binnacle and the closely associated cooling system comprise all of the equipment necessary to mount the platform to the vehicle while providing isolation from thermal and vibratory stimuli induced by the vehicle environment and is illustrated in Figure 3-36 where the three arms of the vibration isolation system can be seen. A photograph of the GSS ADM binnacle is shown in Figure 3-37 and the disassembled binnacle shroud is shown in Figure 3-38. The vibration isolation system is a C-spacing type and is used to minimize any resonance induced jitter, the essential characteristics of which are summarized in Table 3-3. The binnacle temperature control system uses chilled water which is passed through a heat exchanger to cool the surrounding air which, in turn, is forced around and through the enclosed platform by means of a blower and suitable ducting and baffling.

### 3.6 Gravity Sensor Platform (GSP)

The Gravity Sensors Platform (GSP) is illustrated in Figure 3-39 and houses three Gravity Gradient Instruments (GGI's) as shown in the cutaway. An actual photograph of the GSS-ADM platform is reproduced in Figure 3-40.

The Gradiometer Platform (Figure 3-29) is a 3-axis stabilized platform with a conventional gimbal sequence of azimuth inner gimbal, roll middle gimbal, and pitch outer gimbal (pitch and roll being interchangeable depending only on the platform frame orientation within the vehicle). The azimuth axis is capable of continuous rotation. The roll axis has a limited travel of  $\pm 90^\circ$ . Pitch is capable of  $+90^\circ$  and  $-180^\circ$  (the  $180^\circ$  being useful for instrument calibration modes). All gimbals and the platform outer frame are cast aluminum (Alloy A-357) with maximum use of spherical sections for best rigidity and volume utilization. The outer physical envelope is roughly a 25 in. diameter sphere capable of entry through a 25 inch hatch assembled. The all-up assembly weight is 450 lbs including the full payload of instruments, GGI's, and electronics. An orthogonal triad of GGI's is carried on the azimuth gimbal with their spin axes at the "umbrella angle" (i.e., up  $35^\circ$  from the horizontal plane). The azimuth gimbal also carries GGI electronics,

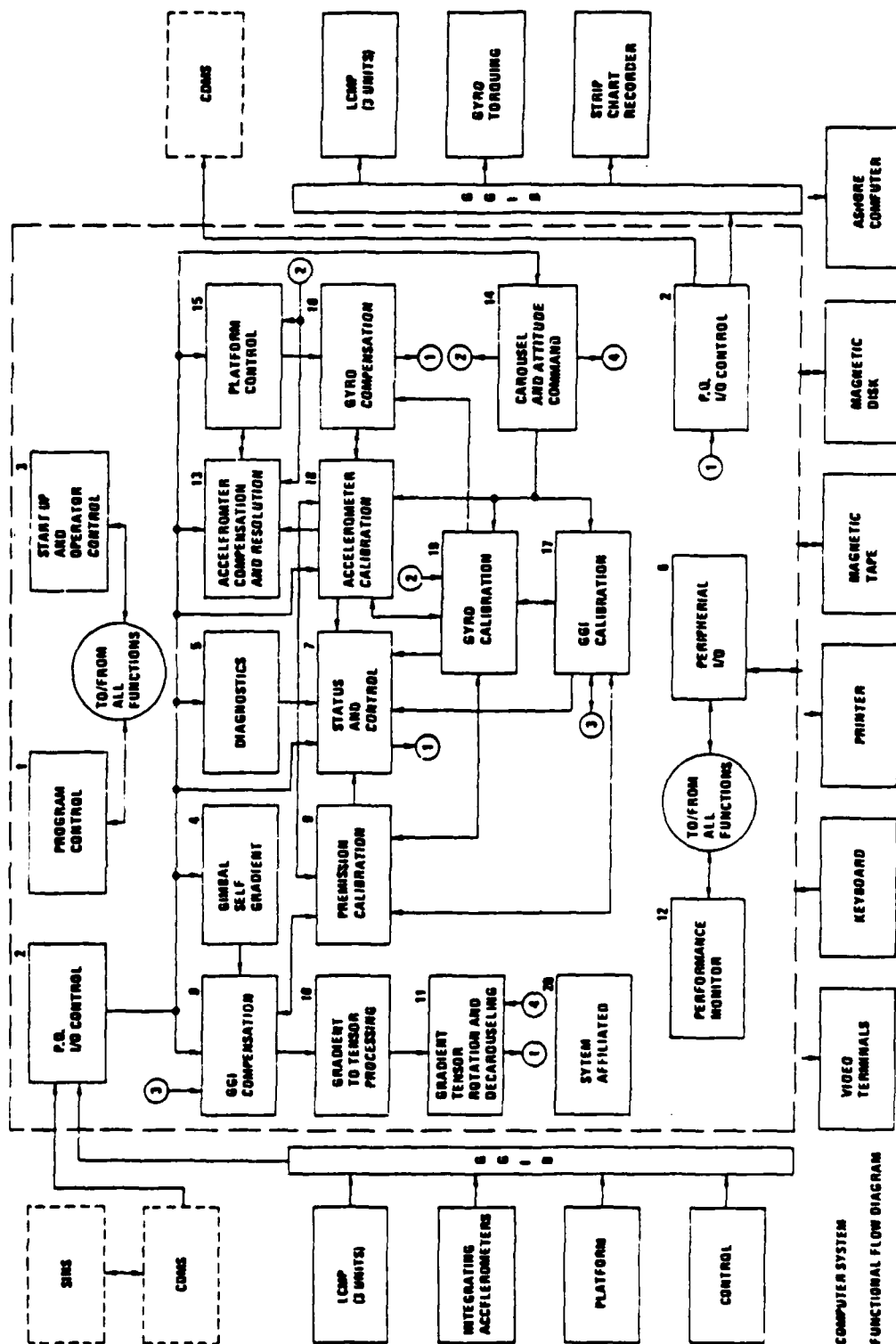


Figure 3-35. DVOC Program



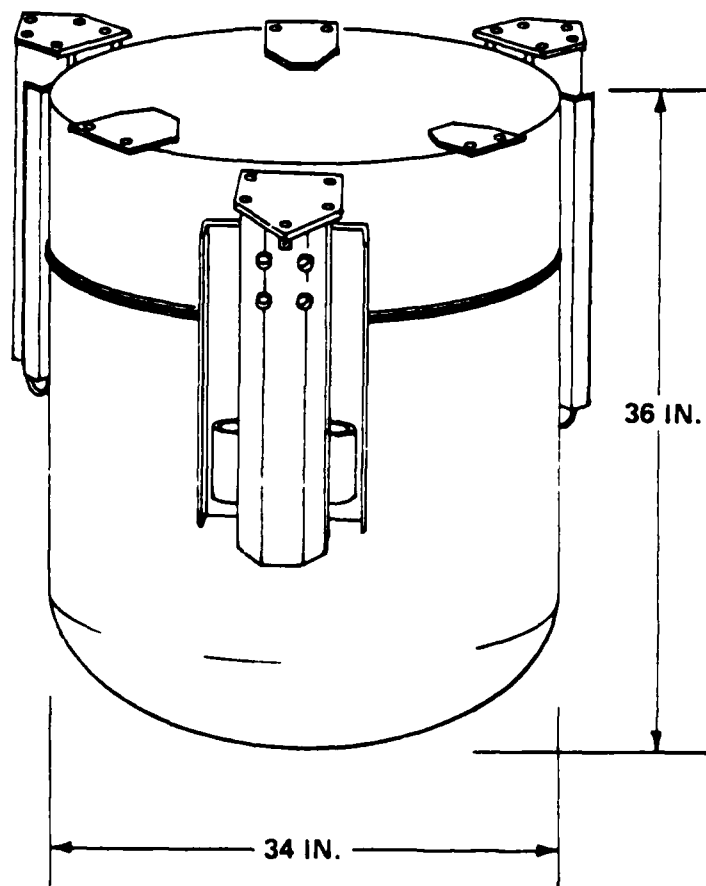


Figure 3-36. Binnacle

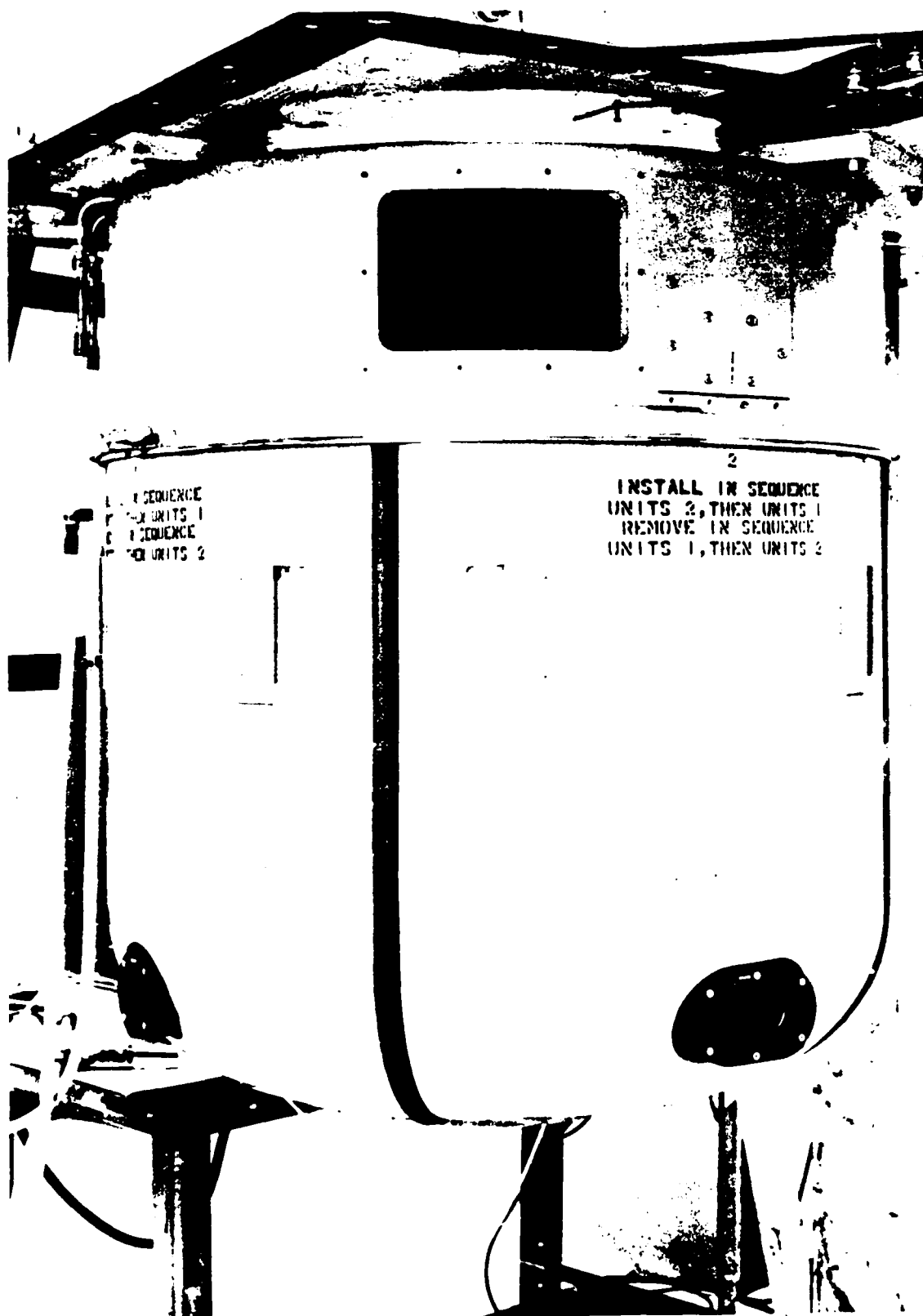


FIGURE 3-37. GSS ADM BINNACLE

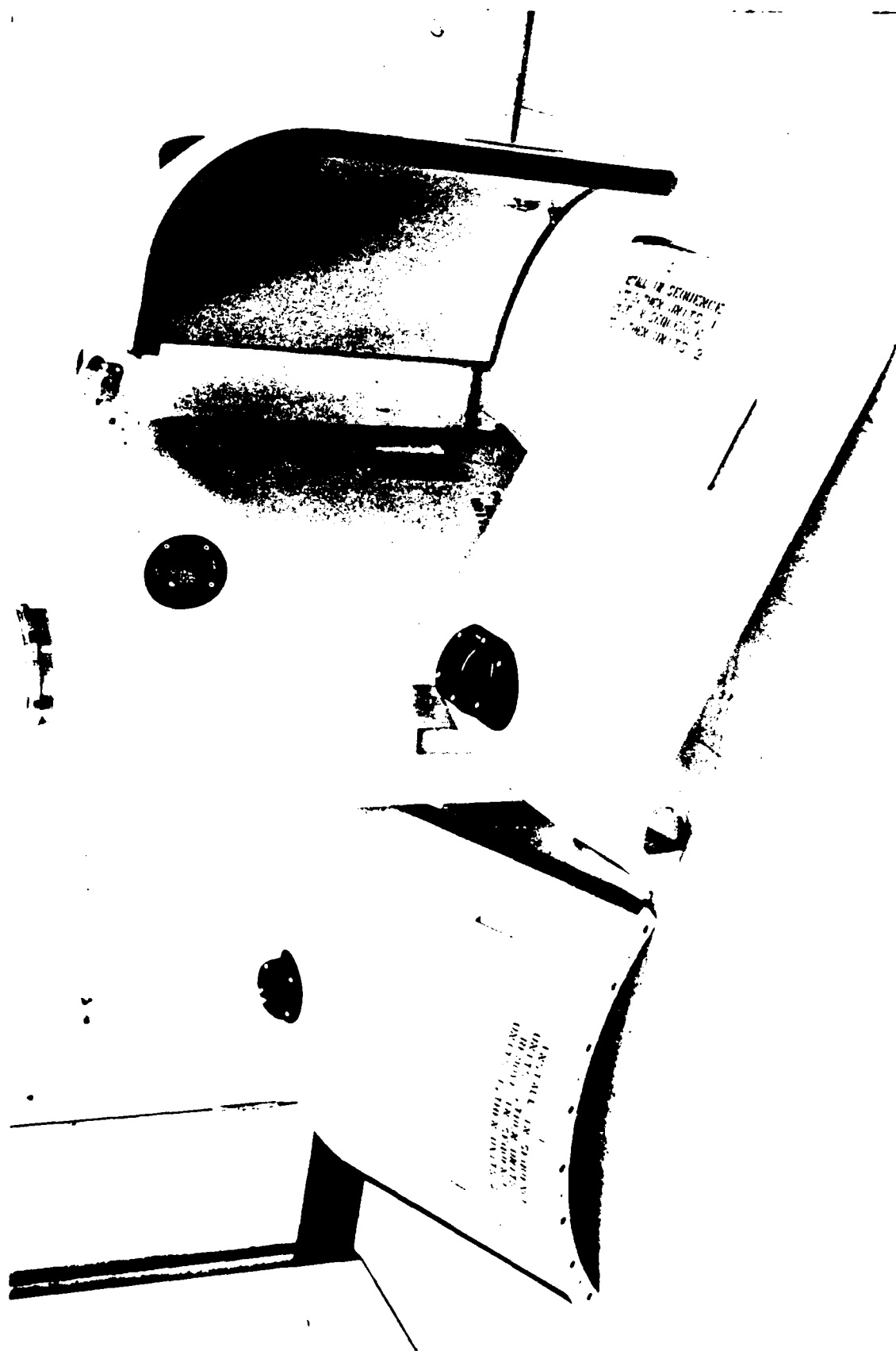


FIGURE 3-38. GSS ADM BINNACLE - DISASSEMBLED

TABLE 3-3

## Vibration Isolator Characteristics for ADM/GSS Platform/Binnacle

ITEM	REMARKS
ISOLATOR NATURAL FREQUENCY	8 Hz LINEAR      } 13 Hz ANGULAR    } (Q $\approx$ 4)
CONFIGURATION	BERYLLIUM COPPER "U-SPRING" ISOLATOR ELEMENTS WITH ADJUSTABLE HYDRAULIC DAMPERS AND MECHANICAL LOCK-UP PROVISIONS
LOCATION	3 ISOLATOR ELEMENTS EQUALLY SPACED AROUND OUTSIDE OF BINNACLE AND LOCATED IN THE C.G. PLANE OF ISOLATED ELEMENTS
TRAVEL	$\pm 0.5$ IN. ALL DIRECTIONS (6 G's, 11 MILLISECONDS, HALF SINE SHOCK REQUIRES 0.32 IN. TRAVEL)
AZIMUTH RETURNABILITY	BETTER THAN 1 MILLIRADIAN
STICTION LOCK-UP	0.1 MILLI-G

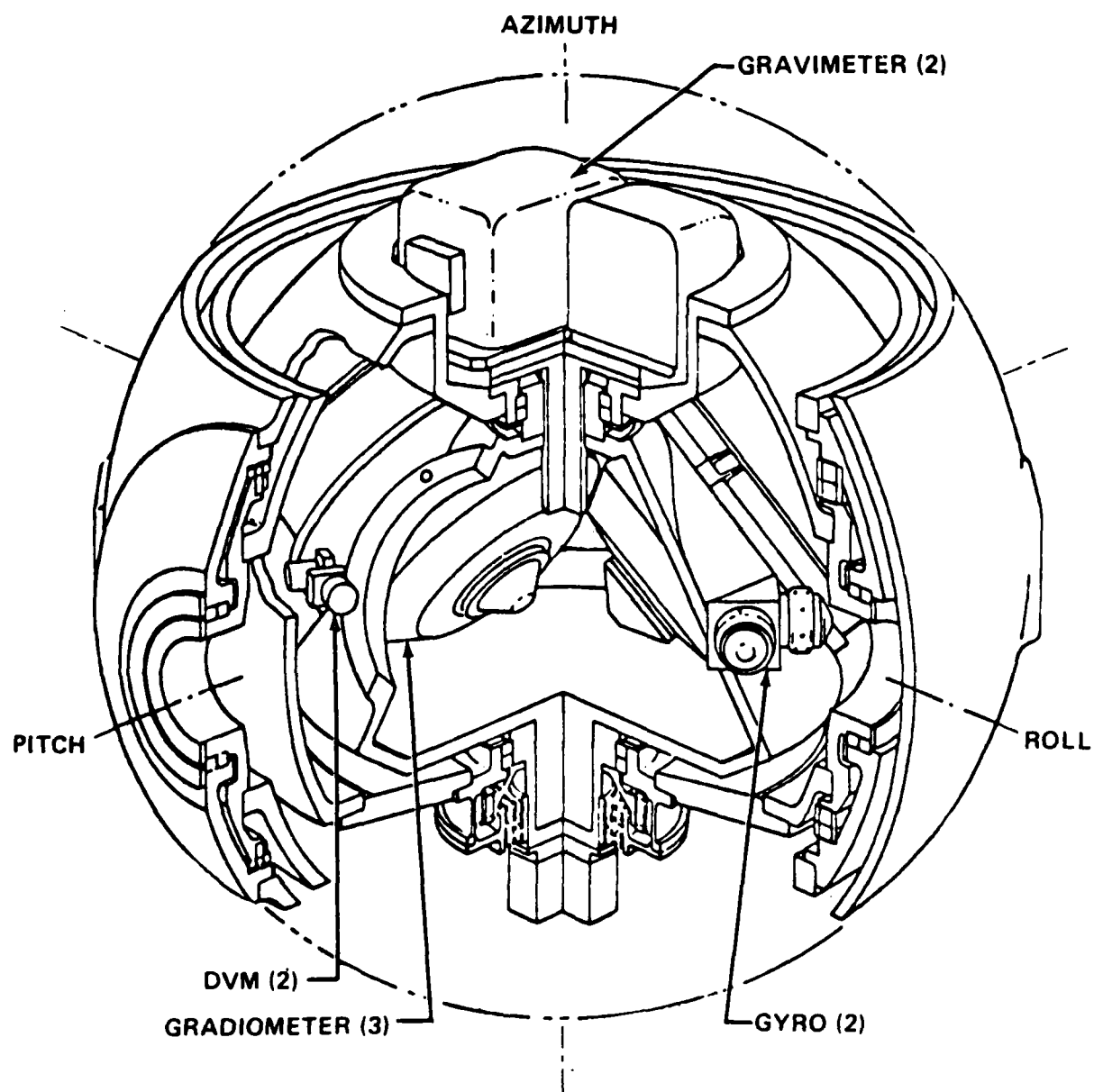


Figure 3-39. Stabilized Platform



FIGURE 3-40. THE GRAVITY SENSORS PLATFORM

gyro and accelerometer sensor assemblies, and gyro constraintment loop electronics. The Platform middle gimbal is designed to mount two Bell Gravimeters and associated electronics.

All Platform axes are supported by conventional duplex-paired ball bearings with controlled preloads for minimum angular stiction. Each axis has a dual-speed (36X, 1X) synchro for angle pick-off and matching the SINS synchros, and a brushless DC torque motor for gimbal torquing in order to minimize any brush torques. The azimuth axis also has a resolver for gyro signal coordinate transformation. Electrical signals are carried across the axes of the platform through a continuous rotation slip ring assembly in azimuth, and limited-travel flex-lead assemblies for pitch and roll. The azimuth slip ring assembly is servoed to minimize stiction and jitter.

The on-platform electronics are limited to only those high frequency servo loops that are otherwise prone to disturbances by slip ring noise and buffer amplifiers. This electronics is modularized and are field replaceable.

Apart from the three GGI's, the platform also carries two Litton G-1200 rate constrained gyros, one to control the leveling axes, the other to control the azimuth axis, and a pair of Bell Model XI leveling accelerometers with pulse rate outputs.

The basic characteristics of this platform are summarized in Table 3-4.

TABLE 3-4  
ADM/GSS Platform Characteristics

ITEM	REMARKS
PLATFORM TYPE	3 AXIS STABILIZED. AZIMUTH INNER GIMBAL, ROLL MIDDLE, PITCH OUTER
GIMBAL TRAVEL	AZ: UNLIMITED, ROLL $\pm 95^\circ$ ; PITCH $+95, -185^\circ$
GIMBAL CONSTRUCTION	CAST ALUMINUM
PLATFORM WEIGHT (ALL-UP WITH PAYLOAD)	390 LB
PLATFORM SIZE	ROUGHLY 2 FOOT DIA SPHERE
STABILIZED INERTIAS	AZ: 11 ROLL: 31 PITCH: 44 (ALL NUMBERS LB-IN. SEC <sup>2</sup> )
GIMBAL BEARINGS	ANGULAR CONTACT, PRELOAD PAIR BALL BEARINGS (MFG KADON DIV OF KEENE, MICH)
GIMBAL AXIS STICTION	17 TO 19 IN.-OZ: ALL AXES
GIMBAL TORQUERS	1000 IN.-OZ BRUSHLESS DC MOTORS: ALL AXES (MFG: MAGNETIC TECHNOLOGY, CALIF)
GIMBAL ANGLE	MULTI-SPEED (1 $\pi$ /36 $\pi$ ) SYNCHRO (20 SEC ACCURACY) FOR ALL AXES. (MFG: CLIFTON PRECISION, PA)
RESOLVER	SINGLE SPEED PANCAKE TYPE (AZ AXIS ONLY) (MFG: CLIFTON PRECISION, PA)
ELECTRICAL ROTARY COUPLINGS	AZ AXIS: 140 CIRCUIT SLIP RING PITCH AND ROLL: $\pm 200^\circ$ FLEX LEAD CAPSULES (MFG POLY-SCIENTIFIC/LITTON, VA)
VERTICAL GYRO	LITTON G1200 0.005°/HR RANDOM DRIFT
AZIMUTH GYRO	LITTON G1200 0.01°/HR RANDOM DRIFT
LEVELING ACCEL	BELL MODEL XI 33 $\mu$ G BIAS REPEATABILITY



### 3.7 Gravity Gradiometer Instrument

Development of the Bell rotating accelerometer gravity gradiometer, also referred to as the gravity gradient instrument (GGI), which is the "heart" of the Gravity Sensors System, was initiated in 1974 under SAMSO funding. The early phases of the project were devoted to demonstrating feasibility at low cost. Initially the achievement of low thermal noise from modified accelerometers was demonstrated, followed by vertical spin axis operation using a GFE precision rate table for the rotation mechanism. Horizontal spin axis performance was demonstrated on the first gradiometer designed as a complete instrument and fabricated in 1976. This instrument was relatively large and employed hydrostatic gas bearings. Incorporated, however, were many of the system techniques essential for the operation of the instrument under moving base conditions. This instrument, referred to as the "baseline" GGI, was tested to formal test procedures in the latter part of 1978. A copy of the Summary Test Report which includes a physical description and functional characteristics of the instrument is included in Appendix C (Volume II).

The use of ball bearings for the GGI rotor was first investigated in a test fixture which was subsequently converted to a fully operating GGI. This unit is referred to as the Ball Bearing GGI Model.

The first GGI designed for platform operation was the AF GGI of which two models were built and tested. The ADM GGI's for the US Navy funded GSS ADM system were very similar to the AF GGI's differing only in relatively minor detail. A total of 8 ADM GGI's similar to those shown in Figures 3-1 through 3-3 were built and tested.

The theory of operation of the Bell GGI is given in detail in Appendix A. The key design features are the use of rotation to modulate the gravity gradients at twice per revolution, and the use of automatic closed loop compensation techniques which provide the moving base capability.

The performance of a gradiometer or gradiometer system is usually expressed by an output error spectrum. In a performance run, this error spectrum is the power spectral density of the output error from all sources. This includes the environment acting on environmental sensitivities and self generated noise.

In the US Navy ADM GSS application, the frequency domain of prime interest is around  $10^{-5}$  rad/sec and to a lesser extent at the Schuler frequency. As illustrated by a typical error power spectral density (PSD), the goal set, under the sponsorship of SAMSO was for a white (or flat) noise level at the high frequency end of the spectrum, of  $10E^2/\text{rad/sec}$ . The Bell rotating accelerometer gradiometer was consequently designed toward that goal.

Figure 3-41 shows typical self generated noise performance obtained on the ADM GGI's together with the minimum which was obtained on ADM GGI S/N 107. Test of the subsystems of the current GGI design indicates the breakdown of white noise sources for a GGI with a  $\frac{1}{2}$  Hz rotor speed, given on Table 3-5.

Source	White Noise Power $E^2/\text{rad/sec}$
Model VII-G Accelerometer Sensor	$\triangle 1$
Model VII-G Constraintment Electronics	$\triangle 1$
Detection Electronics	$\triangle 1$
Electronic Noise in Compensation Loops and Fixed Level Compensation	$\triangle 1$
Total	$\triangle 1$

TABLE 3-5. ADM GGI ERROR ALLOCATION



Data is classified CONFIDENTIAL. See Volume IV Classified Addendum to this report for this page complete with classified data.

The environmental sensitivities of the current GGI design are as listed in Table 3-6.

FIGURE 3-41. ADM GGI SELF GENERATED NOISE POWER SPECTRUM

This figure is classified CONFIDENTIAL. See Volume IV Classified Addendum to this report for this figure.

Environment	Sensitivity
Ambient Temperature	△1
Humidity	△1
Magnetic Fields	△1
Pressure	△1
Linear Vibration at Critical Frequencies 1Ω, 2Ω, 3Ω	△1

TABLE 3-6. ADM GGI ENVIRONMENTAL SENSITIVITIES

The source of the pressure sensitivity is under active investigation and it is anticipated that a design modification will be found to essentially eliminate pressure sensitivity. For the US Navy GSS ADM application, linear vibration sensitivities were specified at △1 but set to △1 or less.

△1 Data is classified CONFIDENTIAL. See Volume IV Classified Addendum to this report for this page complete with classified data.

## 4.0 GRAVITY SURVEY PERFORMANCE ANALYSIS

### 4.1 General

For this analysis the computer algorithms and programs, gradiometer and gravimeter error models, and the earth's statistical gravity model have been defined. In parallel with other IGMS development efforts, these were used to define mission profiles for the categories of vehicles considered for gravity mapping missions and to obtain analytic estimations of the survey accuracies. Preliminary work verify these analytic tools and lead to a first assessment of the accuracies for land based and airborne vehicle surveys using the Bell gradiometer and gravimeter.

### 4.2 Preliminary Analysis, Land Vehicle Surveyor

#### 4.2.1 Scenario

An analysis was conducted to establish the gravity survey accuracy between two known gravity tie points with accuracies of 0.15 arc sec deflection of the vertical and 0.1 and 1.0 mgal. The objective of this analysis was to determine the accuracy of measuring the deflection of the vertical and the vertical components of gravity between the two tie points as a function of vehicle speed, distance between tie points and dwell time at each measurement location.

The conditions and assumptions used for the analysis are outlined on Table 4-1. Neither attitude nor position accuracy are significant performance drivers for land vehicle gravity surveys and the land navigators in operational use are adequate for this application.

TABLE 4-1

GRAVITY SURVEY ACCURACY - VERTICAL DEFLECTION  
GRAVITY SURVEY ACCURACY - VERTICAL COMPONENT  
KALMAN FILTER SMOOTHING ANALYSIS, CONDITIONS AND ASSUMPTIONS

- Gravity Gradiometer/Gravimeter Noise - Predominant Error Source
- Vehicle Velocity: 15 to 80 Knots
- Vertical Deflection Tie Points - 0.15 Arc Second
- Vertical Component Tie Points - 0.1 mgal
- Distance between Tie Points - 20, 40, 80 km
- Dwell Time at Measurement Points - 2 and 4 Minutes
- Gravity Sensor Platform Slaved to Inertial Navigator
- Inertial Navigator Introduces Negligible Attitude and Position Errors (Reasonable Assumption with Land Navigators Available using ZUPTS)
- Models Used: STAG Gravity Model
  - Bell Gravimeter Noise Model
  - Bell Gravity Gradiometer Noise Model

#### 4.2.2 Gradiometer and Gravimeter Error Models

The noise power spectral density models assumed for the gravity gradiometers and gravimeters for this analysis are shown in Figures 4-1 and 4-2, and are based on actual measured data. Both models are characterized by a minus two slope at the low frequencies and a white noise at the higher frequencies. Table 4-2 lists the environmental sensitivities for the gradiometer. The environmental sensitivities of under 1E per OE, 1E per degree F and 5E per milli-g accelerations at the first four harmonics of rotation speed are negligible for relatively benign vehicle conditions such as a truck riding on a smooth road, a ship, and an aircraft at higher altitudes under non-turbulent conditions. Low flying aircraft warrant additional considerations.

TABLE 4-2

ROTATING ACCELEROMETER GRAVITY GRADIOMETER INSTRUMENT CHARACTERISTICS ASSUMED

<u>Performance</u>	<u>Frequency (Rad/Sec)</u>	<u>Power Spectral Density (E<sup>2</sup>/Rad/Sec)</u>
Self Generated Noise	10 <sup>-1</sup>	25
	10 <sup>-2</sup>	25
	10 <sup>-3</sup>	35
	10 <sup>-4</sup>	1×10 <sup>3</sup>
Magnetic Sensitivity		<1E/Oe
Temperature Sensitivity		<1E/ <sup>o</sup> F
Linear Acceleration Sensitivity at 1, 2, 3 and 4 Times Spin Speed		<5E/Millig

FIGURE 4-1. GGI SELF GENERATED NOISE PSD ASSUMED FOR INTEGRATED GRAVITY MAPPING SYSTEM

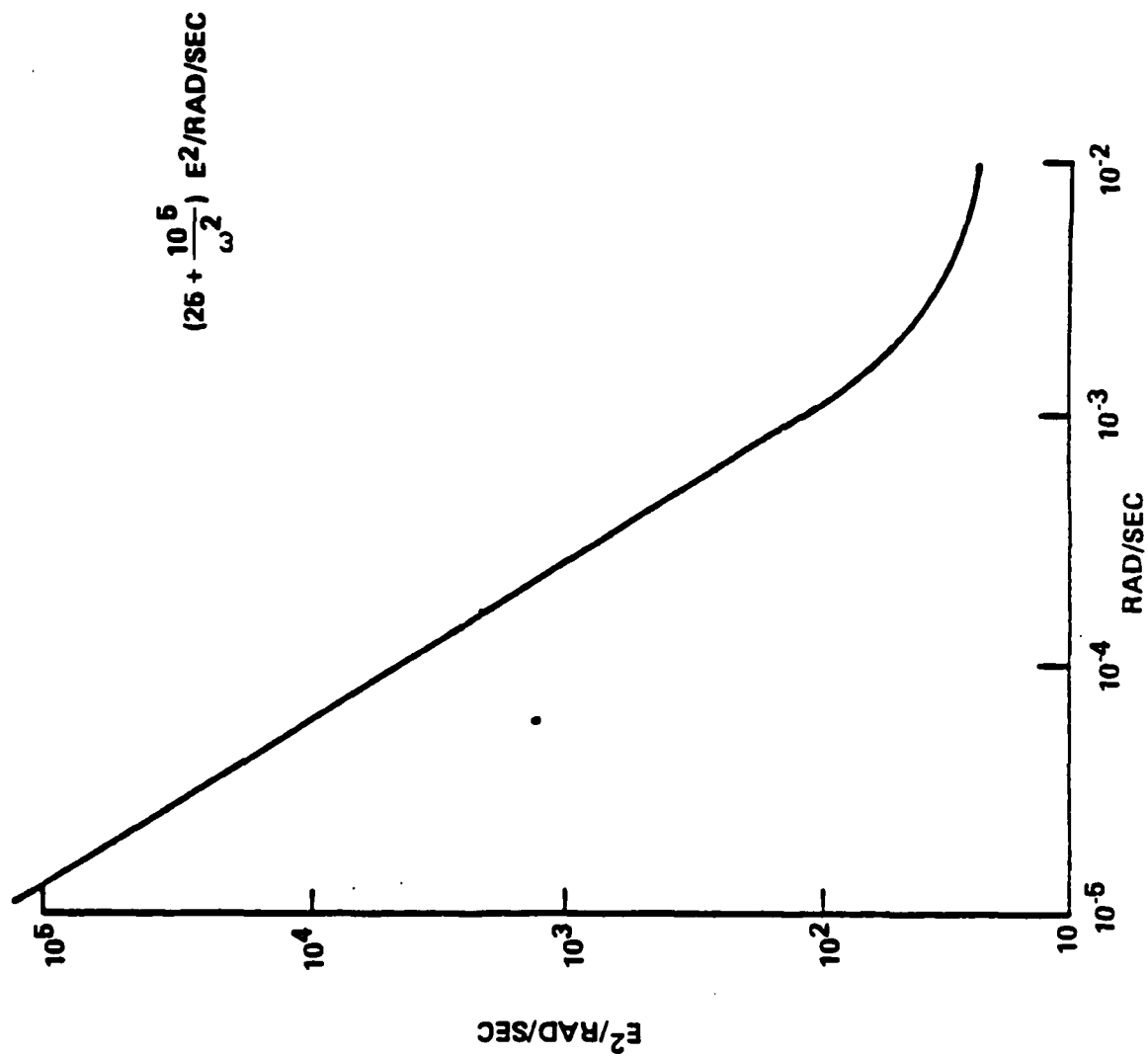
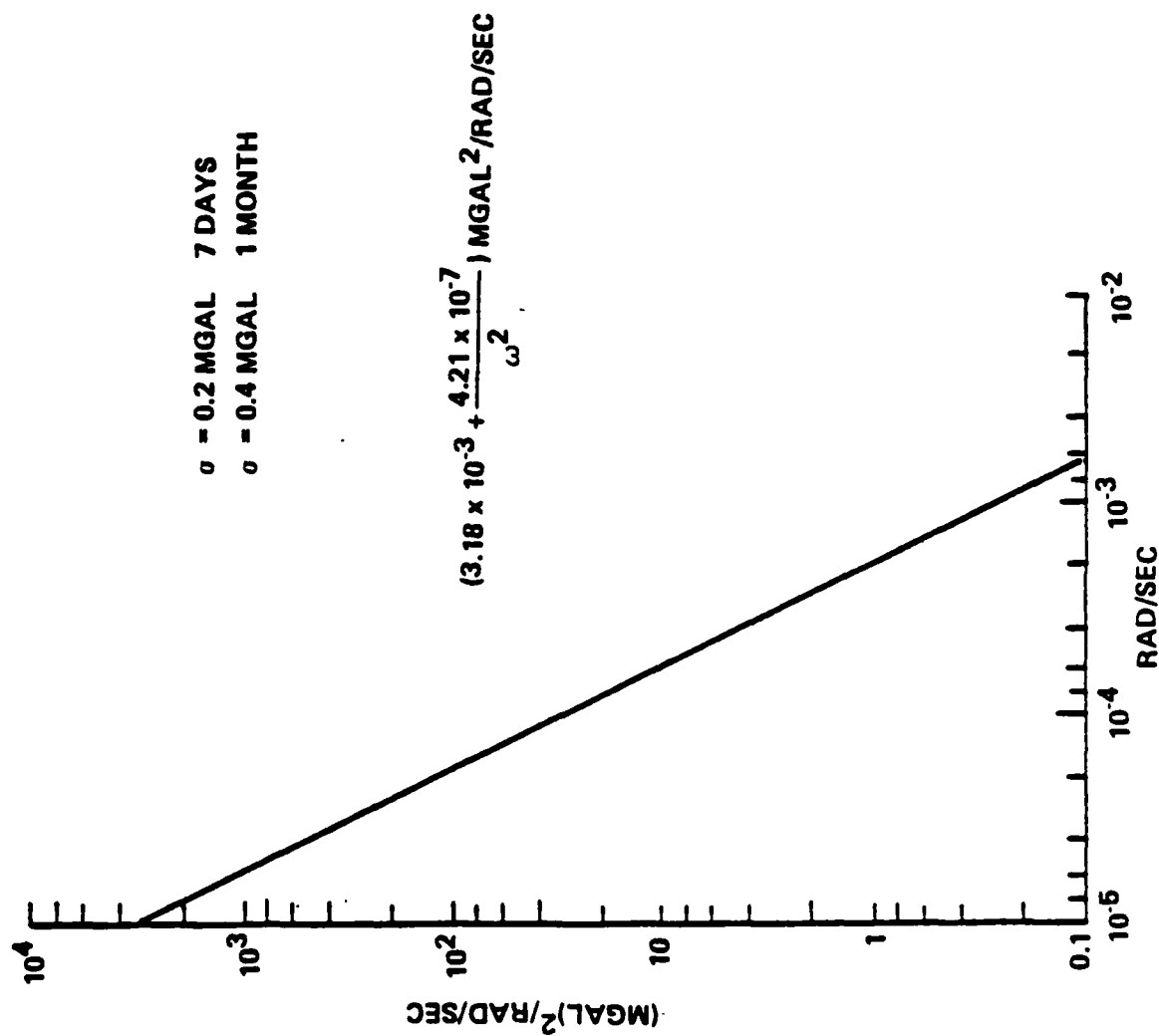


FIGURE 4-2. GRAVIMETER SELF GENERATED NOISE PSD ASSUMED FOR INTEGRATED GRAVITY MAPPING SYSTEM





#### 4.2.3 Method of Analysis

A simplified block diagram of the Kalman filter smoothing filter used for the analysis is illustrated on Figure 4-3. Elements of the gravity sensor Kalman filter are:

- (1) Gravity process - The actual process  $x$  consisting ( $T_x, T_y, T_z, T_{xx}, T_{zy}$ , etc.) encountered along the vehicle trajectory.  $T_x, T_y$ , and  $T_z$  are the components of the gravity vector, and  $T_{xx}, T_{zy}$ , etc. are elements of the second order tensor - the gravity gradient tensor elements.
- (2) Estimate of the gravity process  $\hat{x}$  consisting of ( $\hat{T}_x, \hat{T}_y, \hat{T}_z, \hat{T}_{xx}$ , etc.).
- (3) Dynamics of the gravity process model which characterize its behavior with position along the vehicle's trajectory. The model is a state space approximation to a statistical characterization of the process.
- (4)  $C_A^U$  - Indicates a coordinate transformation from along track-cross track coordinates into instrument coordinates.
- (5) Output matrix which relates a component of the predicted output error  $\tilde{Y}$  linearly to an error in the estimate of the gravity process  $\tilde{X}$ .
- (6) The remaining component of the predicted sensor output error  $\tilde{Y}$  is characterized by the sensor estimation error  $\tilde{X}_I$ .
- (7) The sensor prediction error  $\tilde{Y}$  is multiplied by the optimal gain matrix to provide corrections to the gravity process model  $\hat{X}_p$  and to the instrument model  $\hat{X}_I$ .

$$\tilde{X}_p = \hat{X}_p - X_p - \text{error of process estimate}$$

$$\tilde{X}_I = \hat{X}_I - X_I - \text{error of instrument process estimate}$$

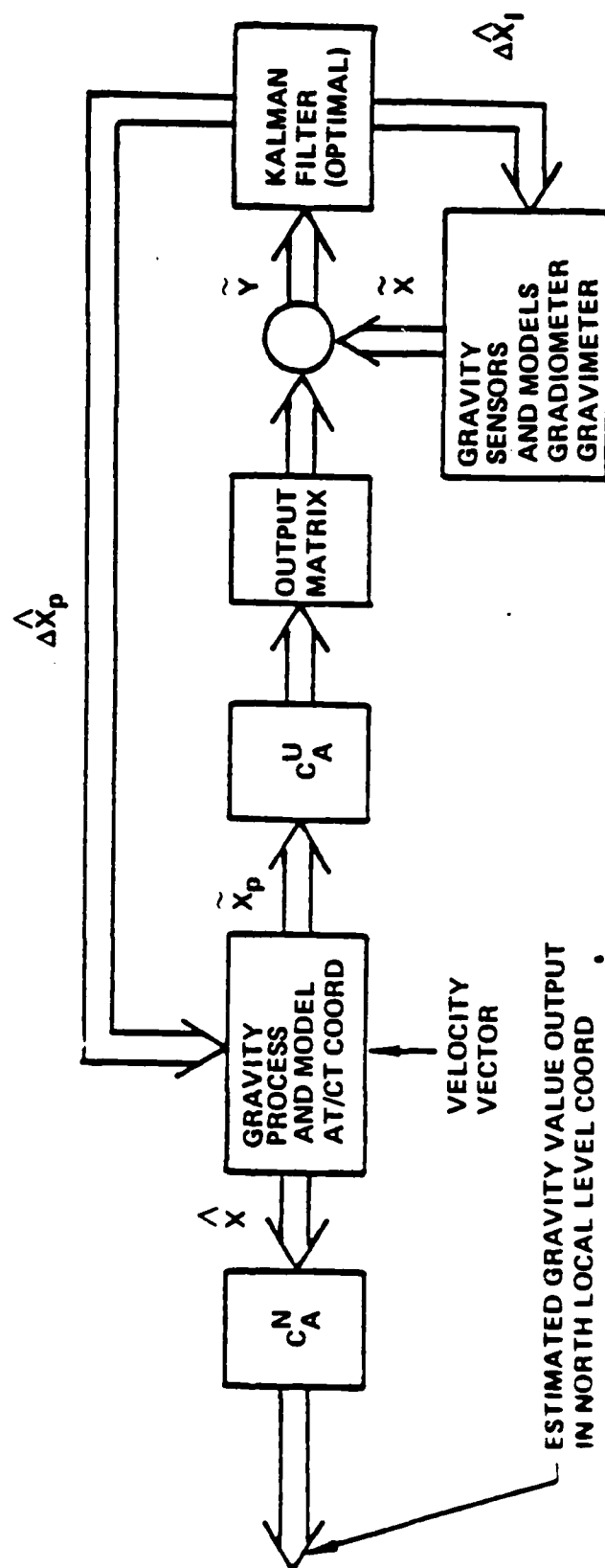
$$\hat{X}_p = \text{gravity process estimate } (\hat{T}_x, \hat{T}_y, \hat{T}_z, \hat{T}_{xx} \text{ --- etc.})$$

$$\hat{X}_I = \text{estimate of gravity sensor errors (bias, low frequency noise, etc.)}$$

$$X_p = \text{states of actual gravity process}$$

$$X_I = \text{states of actual instrument errors}$$

FIGURE 4-3. BLOCK DIAGRAM IGMS KALMAN FILTER



NO-A179 100

INTEGRATED GRAVITY MAPPING SYSTEM (IGMS) STUDY PROGRAM  
FOR AIRCRAFT AND L. (U) BELL AEROSPACE TEXTRON BUFFALO  
NY E H NETZGER ET AL. MAR 82 6487-927004-VOL-1

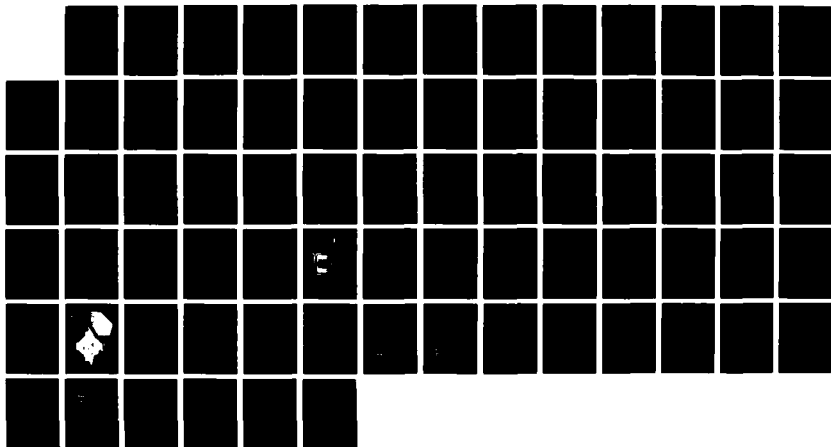
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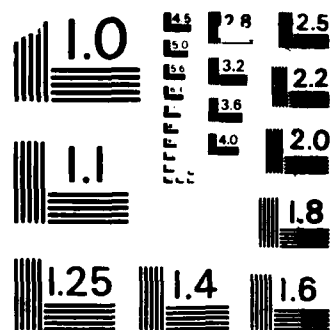
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MICROCOPY RESOLUTION TEST CHART  
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#### 4.2.4 Discussion of Results

Figures 4-4 and 4-5 present the along track and across track deflection of the vertical accuracies for locations between two gravity survey points. Tie point separation distances of 40 and 80 km were used with both the nominal GGI noise power and  $100 \times$  GGI noise power. The deflection of the vertical accuracies obtained approximates the tie point accuracy for all positions along the track. Using  $100 \times$  GGI noise power, not surprisingly, shows the poorest deflection data midway between the tie points. The relationship between the midpoint deflection of the vertical for the 80 km track distance and multiples of nominal GGI noise is illustrated on Figure 4-6. The midpoint deflection accuracy deteriorates as a power function of between 0.3 and 0.4 multiples of GGI nominal noise. Thus, the preliminary analysis indicates that GGI noise is a rather weak driving force on vertical deflection accuracy and, if substantiated by the detailed, exact analysis in progress, little would be gained by specifying a GGI noise lower than the  $25E^2/\text{rad/sec}$  presently obtainable unless much longer traverses are planned. However, BAT's ongoing program to identify and correct error mechanisms is expected to consistently yield instruments with noise levels below  $10E^2/\text{rad/sec}$ .

For the nominal gravity gradiometer and gravimeter noise, the vertical gravity anomaly determination at all positions between the two tie points is about 0.066 mgal, or somewhat better than each tie point accuracy because of averaging effect of the two tie points. Figure 4-7 illustrates the nominal GGI noise power and illustrates the importance of the gradiometer for the vertical anomaly determination.

#### 4.2.5 Summary and Conclusions, Land Vehicle Surveyor

The conclusions of this analysis for the land based application are summarized on Table 4-3. The addition of a gravity sensor system to a land based position surveying system would, with the performance levels of existing Bell gravity gradiometer and gravimeter instruments, permit high speed deflection of the vertical determinations to a fraction of an arc second and vertical gravity measurements to a fraction of a milligal. In the next section, extension of the analyses, shows that these conclusions are also valid for airborne surveys.

FIGURE 4-4

**ALONG TRACK DEFLECTION BETWEEN TIE POINTS AS FUNCTION OF  
DISTANCE BETWEEN TIE POINTS AND GGI NOISE**

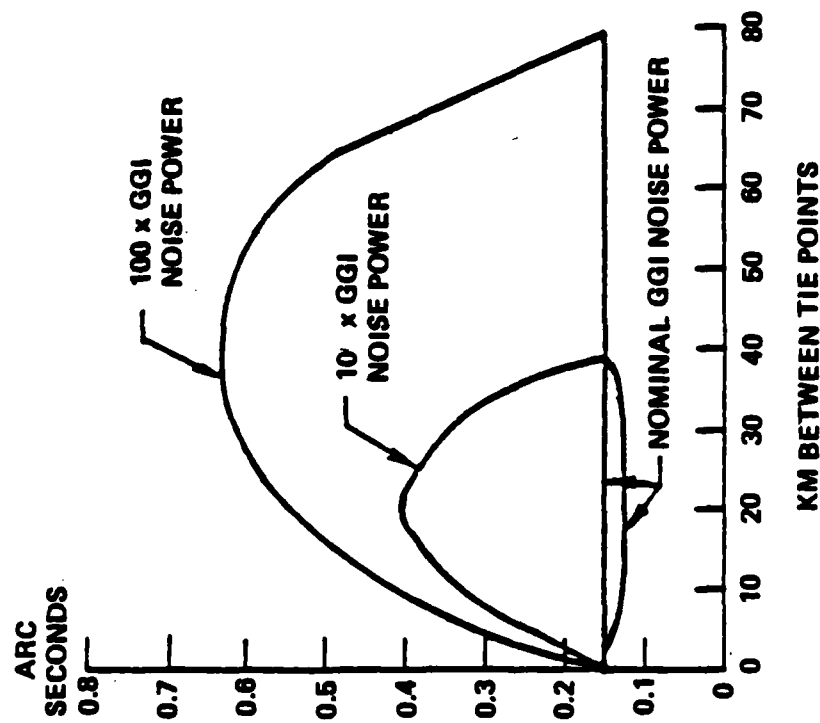


FIGURE 4-5  
**CROSS TRACK DEFLECTION BETWEEN TIE POINTS AS FUNCTION OF  
 DISTANCE BETWEEN TIE POINTS AND GGI NOISE**

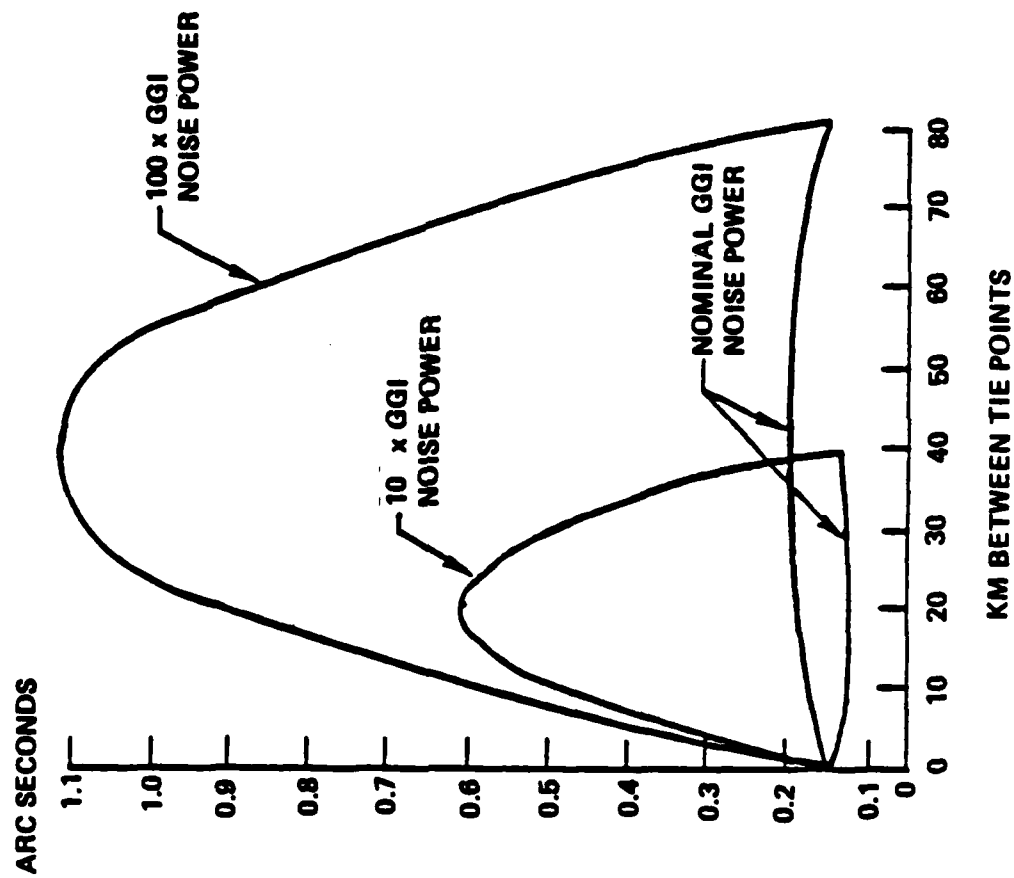


FIGURE 4-6

**MID POINT DEFLECTION OF VERTICAL AS FUNCTION OF GGI**  
**NOISE POWER 80 KM BETWEEN GRAVITY POINTS**

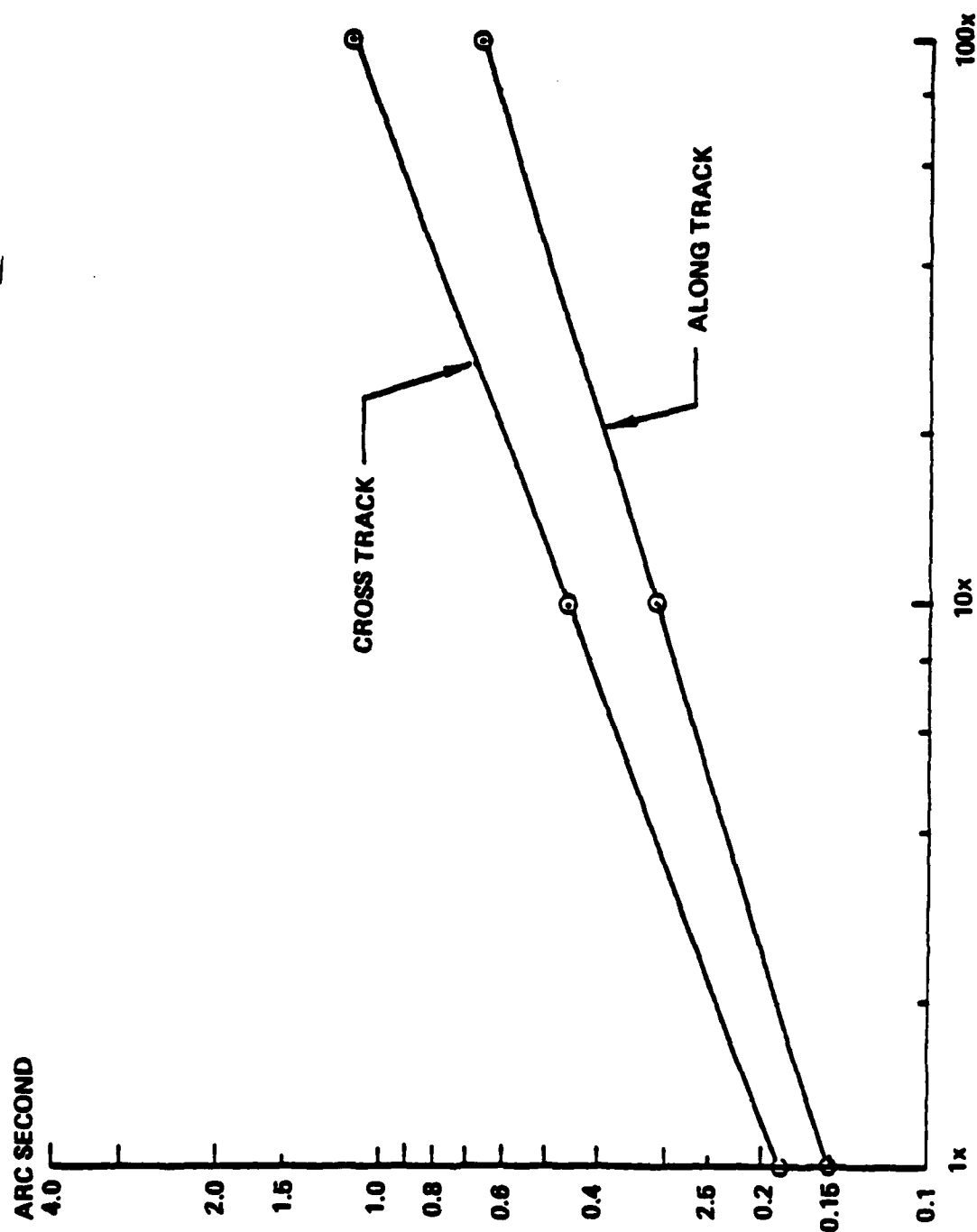




FIGURE 4-7

VERTICAL GRAVITY ANOMALY ACCURACY AS FUNCTION OF GGI  
NOISE POWER (80 NMI DISTANCE BETWEEN THE TIE POINTS)

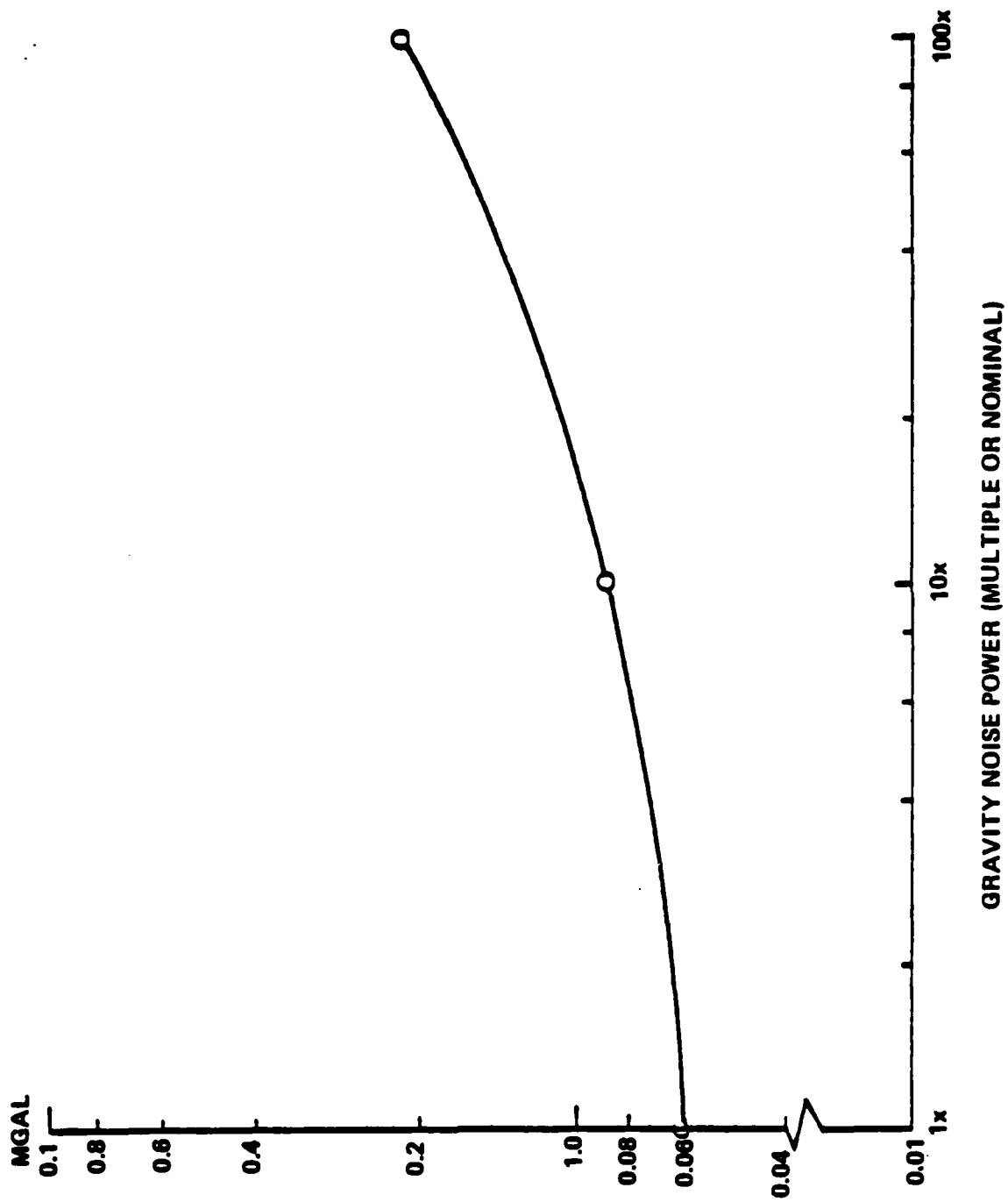


TABLE 4-3

CONCLUSIONS OF ANALYSIS FOR THE LAND BASED IGMS APPLICATION

- The deflection of the vertical and the vertical gravity anomaly can be measured to the accuracy of the gravity tie points at either end of an 80 km track with the Bell GGI and gravimeter.
- The maximum deflection of the vertical error occurs midway between tie points. This error increases approximately as the 0.35 power of GGI noise power and approximately as the 0.7 power of separation distance.
- The along track deflection measurements are approximately 50% more accurate than the cross track deflection measurements.
- GGI bias is compensated by the gravity survey tie points.
- Vehicle velocity between 20 and 80 knots and dwell times between 2 and 4 minutes have no significant impact on the deflection of the vertical and vertical gravity accuracy.
- The gravity gradient measurements significantly improve the determination of the vertical gravity anomaly. The inclusion of a gravity meter does not significantly improve the deflection of the vertical measurements.

4.3 Preliminary Analysis, Airborne Surveyor

4.3.1 Introduction

For this report an analysis was conducted based on the extrapolation of a single dimensional gravity field analysis which used Wiener smoothing and the SSM three-dimensional algebraic gravity model. The assumption that the North-South and East-West tracks can be treated independently was made. Least square collocation of all crossing points of tracks was applied. It is realized that this analysis approach is not sophisticated, but did yield results in a short period of time which are believed to be representative of what can be achieved.

The flight path pattern assumed consisted of two flights around the perimeter of the 30x30 nautical mile area to be gravity mapped, followed by orthogonal tracks with 3 nautical mile spacing. The criteria for selecting the traverse grid are discussed in Section 4.3.2 and the analysis method and results are discussed in Section 4.3.3.

Conclusions obtained from this analysis indicate that the worst case error obtained is 0.26 milligals (0.05 arc sec) standard deviation in transfer of the vertical deflection, substantially less than the basic requirement of 1 milligal (maximum). Based on the selected grid density of three mile separation between survey points, the flight time, rather than error buildup, was found to be the factor which limits the survey area size.

The study determined simple "rules of thumb" which are useful for quickly extending the results of other candidate flight paths. These are summarized in Section 4.3.3.2.6.

In Section 4.3.3.2.7, the results were extended to increased survey area sizes by lowering the grid density. Limitations imposed by variations in GGI self generated noise, flight time, and maximum allowable error were also evaluated.

#### 4.3.2 Description of Survey Traverse

The objectives of the survey traverse selection are to choose traverses which assure high survey accuracy and which maximize the area surveyed during a mapping flight. A model traverse was formulated which attains these objectives by:

- (1) Efficient use of those points along the flight path which have high survey accuracy as tie points to increase the accuracy of the other points by using post-mission smoothing.

- (2) Minimizing aircraft maneuvers. This provides a potential for increasing the survey area since maneuvers constitute a non-productive increase in flight time. Survey accuracies are further increased because of the reduction in time (distance) between survey points and tie points. Traverses which minimize excess maneuvers also minimize the potential for flight path deviations from the planned profile.

The model traverse has four distinct phases. These phases blend together with smooth transitions between phases, consistent with the objective of simple maneuvers. These phases are illustrated in Figure 4-8A through D. Table 4-4 summarizes the features of the trajectory.

#### 4.3.3 Error Analysis, Airborne Surveyor

##### 4.3.3.1 Simulation Results for Straight Line Traverse (SLT)

Figures 4-9 and 4-10 summarize the results of a complete computer simulation using the Sperry Three-Dimensional Algebraic Gravity Model (STAG) and Wiener filter smoothing. Three gravity gradiometer instrument self noise PSD's were evaluated. These are defined below and are identified in this report by their floor noise levels of  $25E^2/\text{rad/sec}$ ,  $10E^2/\text{rad/sec}$ ,  $2E^2/\text{rad/sec}$

$$\text{PSD}_1 = \frac{10^{-5}}{\omega^2} + 25 E^2/\text{rad/sec} \quad (1)$$

$$\text{PSD}_2 = \frac{10^{-5}}{\omega^2} + 10 E^2/\text{rad/sec} \quad (2)$$

$$\text{PSD}_3 = \frac{2 \times 10^{-8}}{\omega^2} + 2 E^2/\text{rad/sec} \quad (3)$$

These three GGI noise models represent: (1) the present Bell GGI, (2) the improved Bell GGI in the near future, and (3) the projected performance believed achievable.

The flight conditions assumed for this analysis were:

- Straight Line Traverse (SLT)
- Constant Velocity of 200 knots
- 25,000 ft Altitude

##### 4.3.3.2 Extension of SLT to Two-Dimensional Mapping

###### 4.3.3.2.1 General

The results of Section 4.3.3.1 (Figures 4-9 and 4-10) are extended to two-dimensions by approximate analysis. Exact analysis which is underway, using a multidimensional model of the earth's gravity potential field such as the STAG model and optimal two-dimensional post mission data smoothing, are expected to show error estimates which are less than the errors which are obtained by the approximate method. Because the results are conservative and will be shown to yield transfer of the deflection of the vertical to substantially

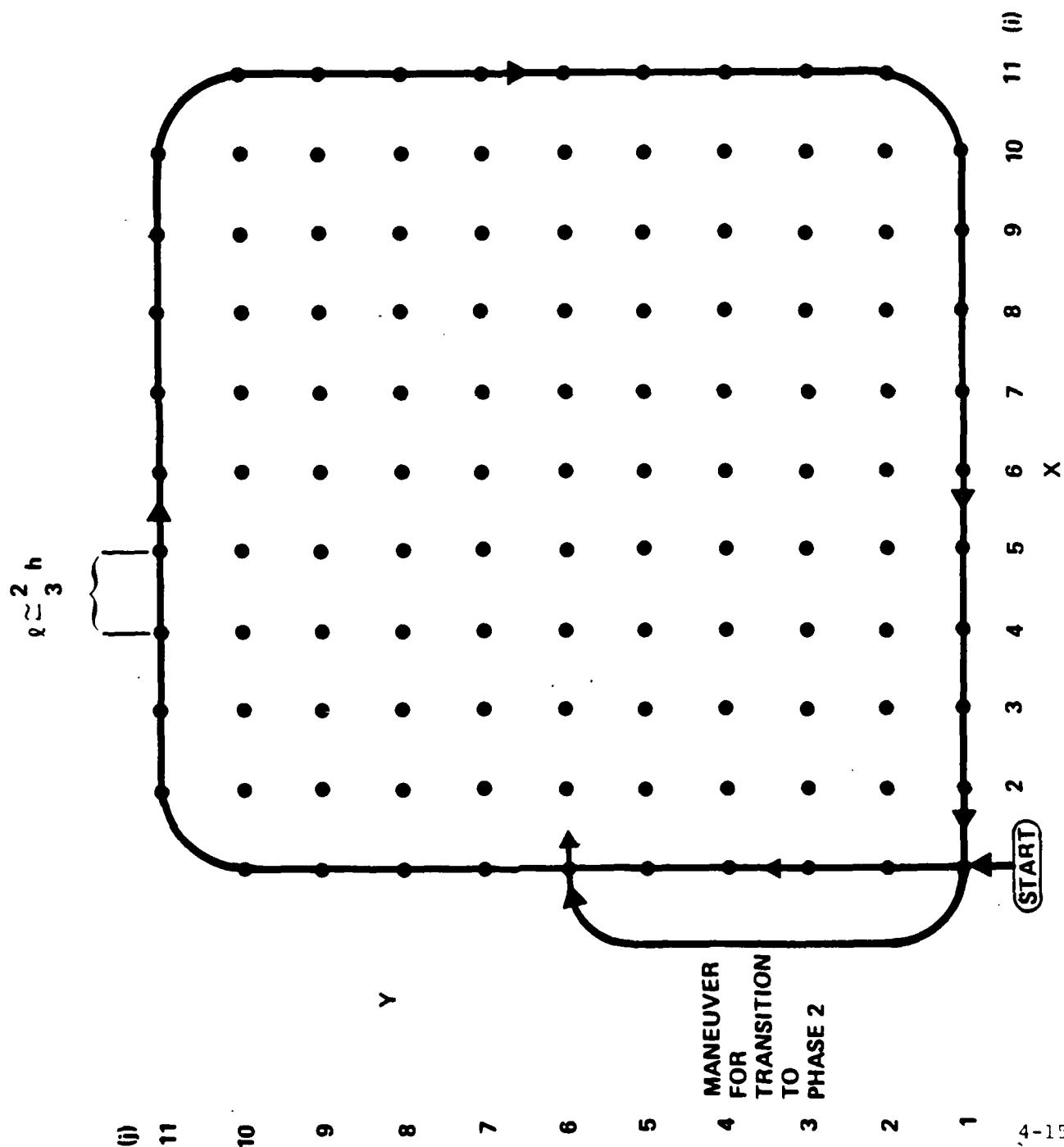
FIGURE 4-8A

MODEL SURVEY  
TRAVERSE

PHASE 1

INITIAL PERIMETER  
TRAVERSE

(POINT (1, 1) IS BASIC  
REFERENCE TIE POINT)  
ALL RADII =  $\ell$



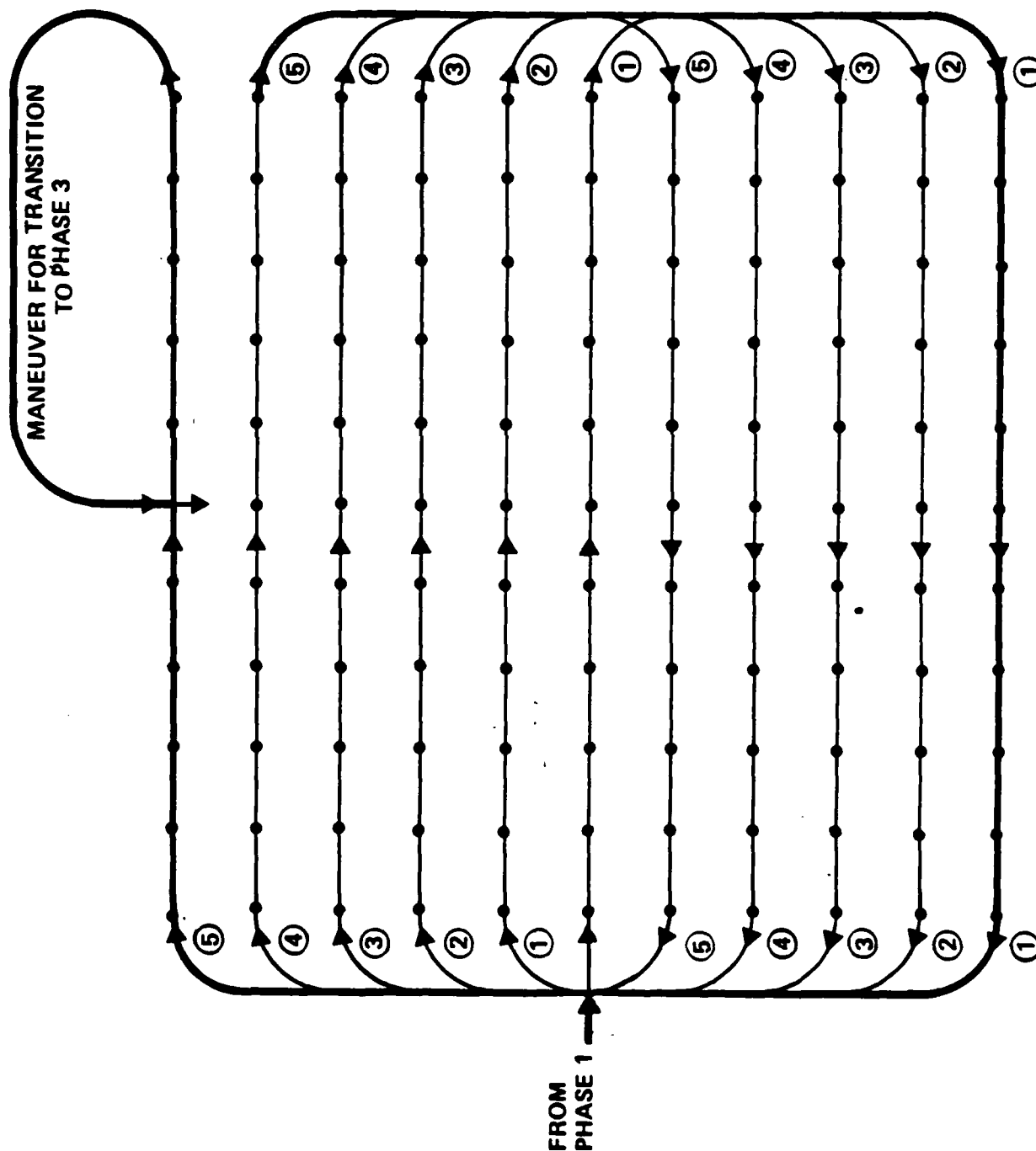


FIGURE 4-8B  
 MODEL SURVEY  
 TRAVERSE  
 PHASE 2  
 LATERAL GRID  
 TRAVERSE  
 [ENTERED AT (1, 6)]  
 ALL RADII =  $\rho$

FIGURE 4-8C  
 MODEL SURVEY  
 TRAVERSE  
 PHASE 3  
 LONGITUDINAL  
 GRID TRAVERSE  
 [ENTERED AT (6, 11)]  
 ALL RADII =  $\ell$

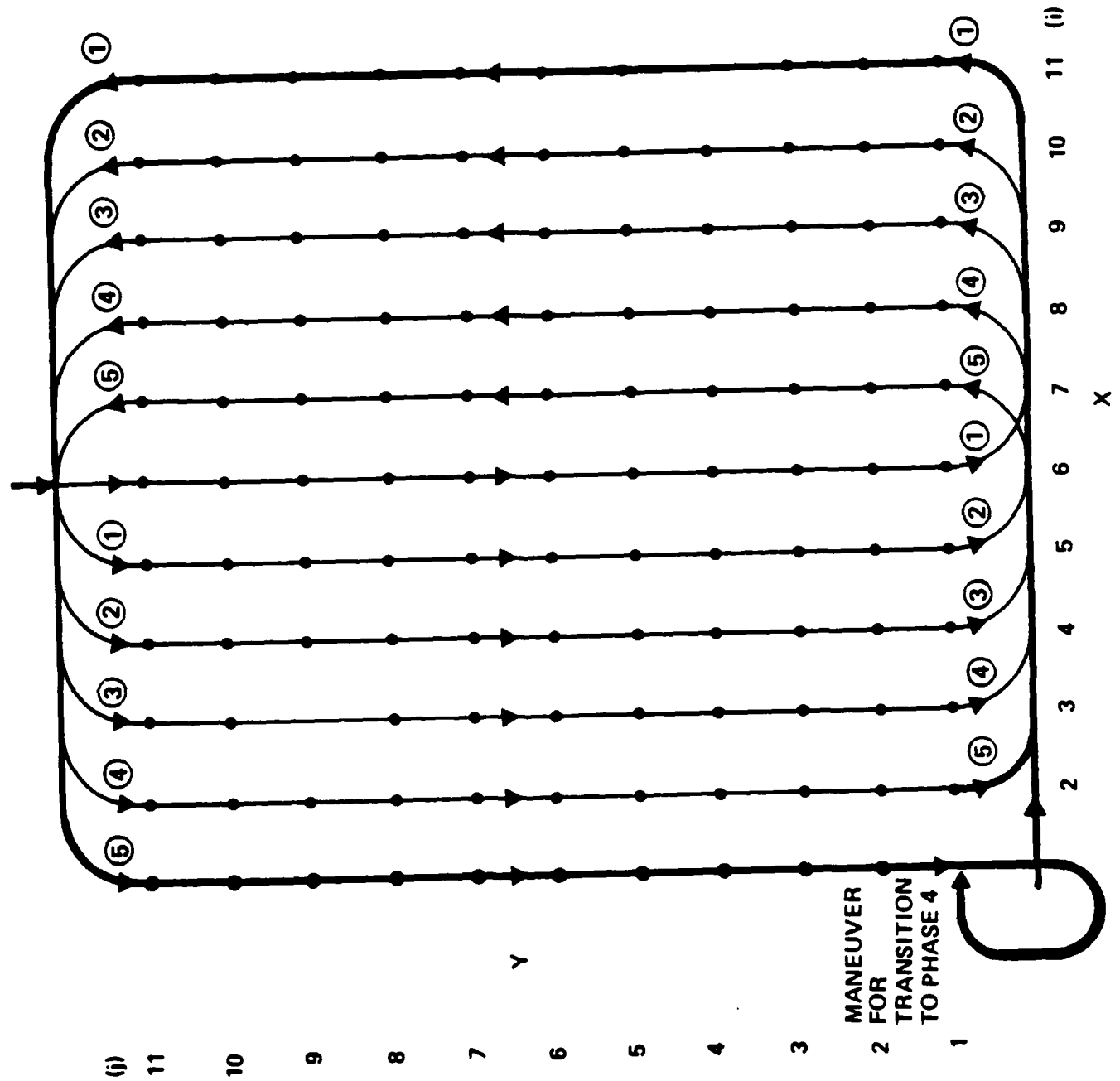


FIGURE 4-8D

MODEL SURVEY  
TRAVERSE

PHASE 4

MISSION CONCLUSION  
PERIMETER TRAVERSE  
[ENTERED AT (1, 1)]

ALL RADII =  $\ell$

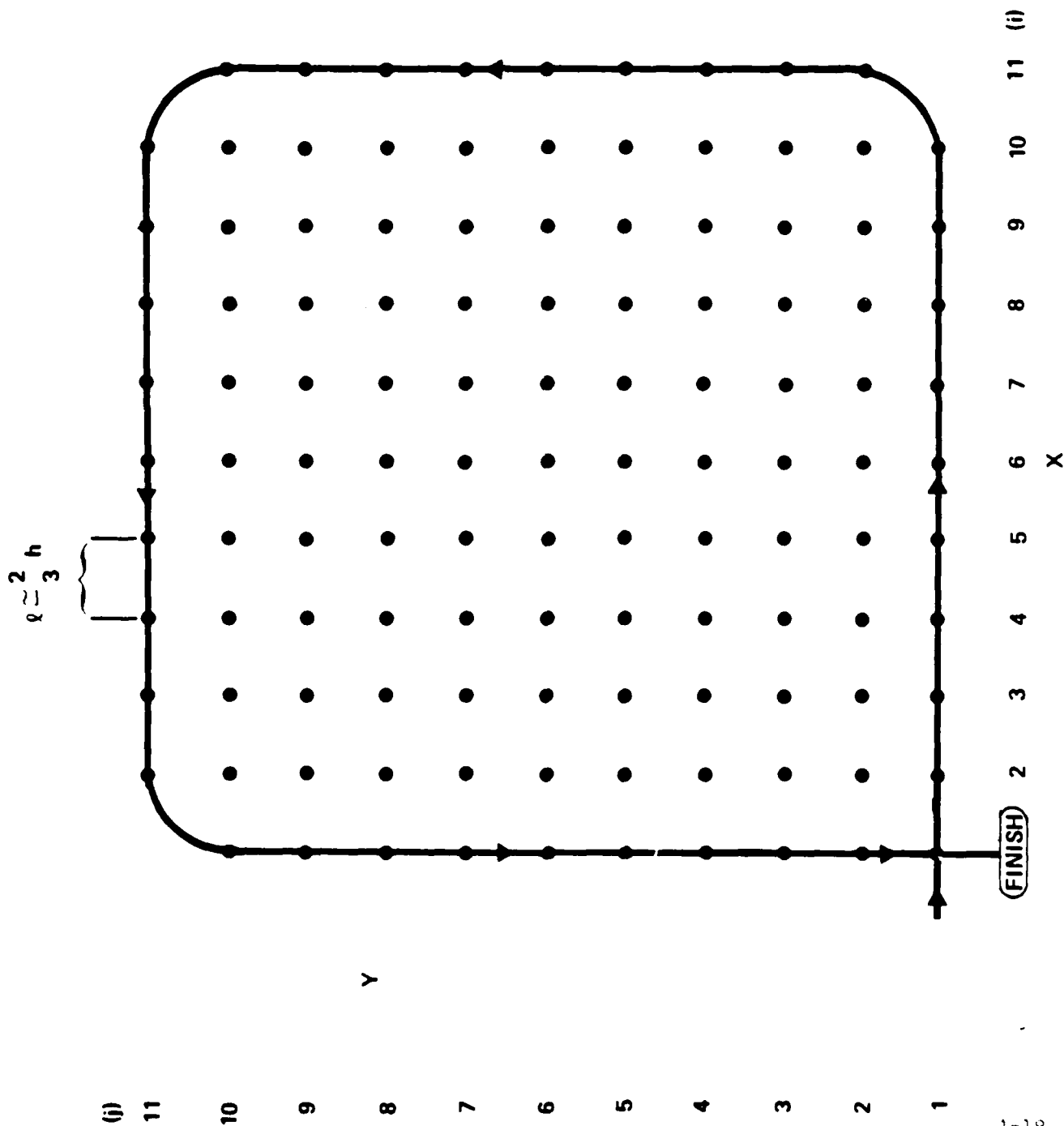




TABLE 4-4

MODEL TRAVERSE CHARACTERISTICS

- Transfers deflection of vertical from basic reference point (1,1) to 120 new positions.
- Survey area is a square 30 NM to a side.
- Grid spacing is 3 NM.
- Survey points of high precision are established along the perimeter by two perimeter traverses in opposite directions. The perimeter points are post-mission error corrected by closures on the basic reference point.
- Grid points in the interior are error corrected by closures with the high precision perimeter points (4 closures for each interior point).
- Traverse length  $\approx$  1400 NM. Mapping time  $\approx$  7 hours at 200 knots.

FIGURE 4-9  
ALONG TRACK DEFLECTION

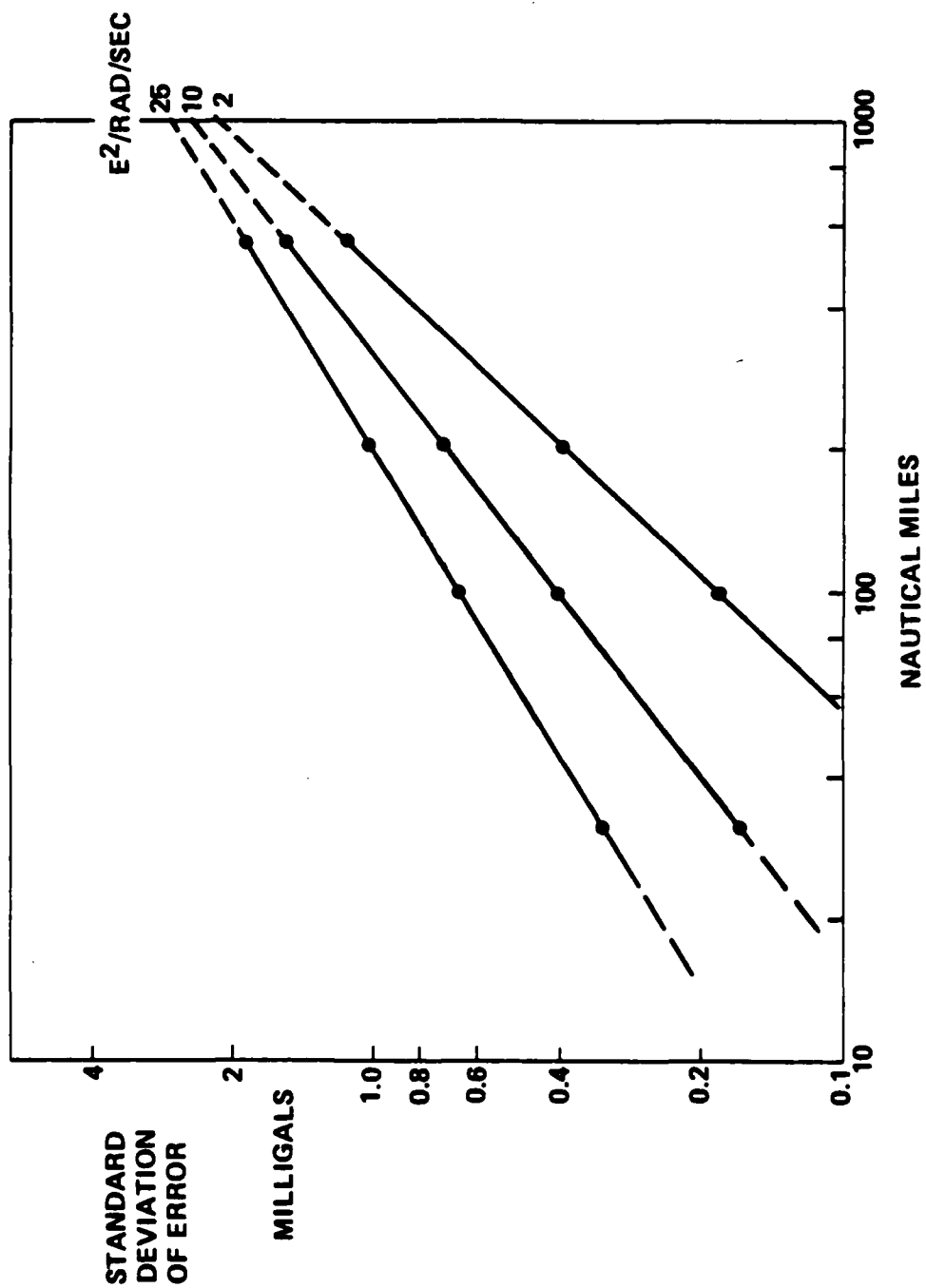
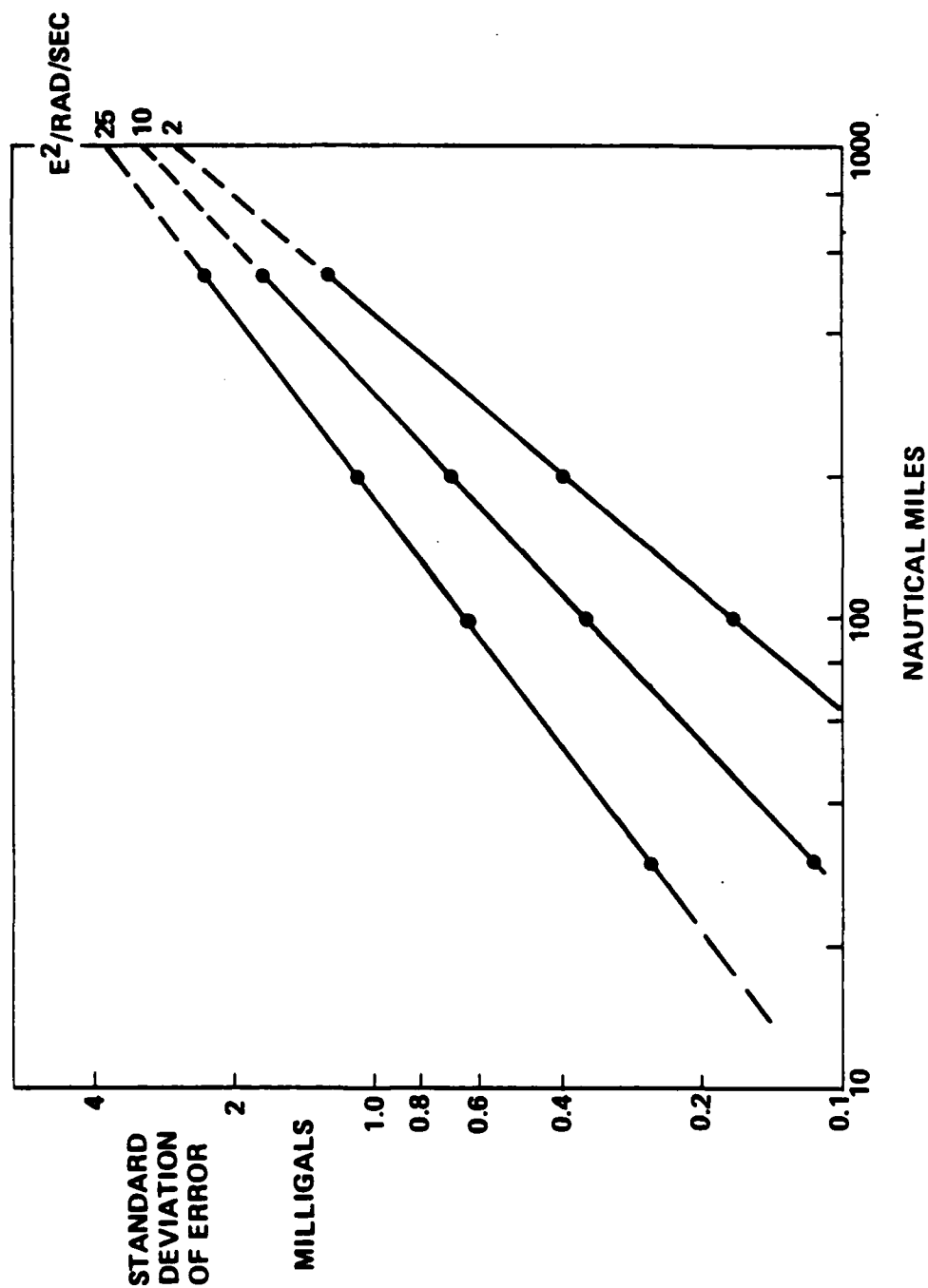


FIGURE 4-10.

CROSS TRACK DEFLECTION



less than the requirement of 1 milligal (0.2 arc sec), the use of the approximate method is justified by the large saving of time in analysis and computer operation. The flexibility of the approximate method enables rapid analyses and "rule of thumb" assessments of many combinations of candidate trajectories.

A curve fit of the results of the exact analysis for the straight line traverse from the simulation described in Section 4.3.3.1 (shown in Figures 4-9 and 4-10) was performed for the three levels of GGI self noise Power Spectral Density (25, 10,  $2E^2$ /rad/sec). This curve fit shows that the standard deviation (expressed in milligals) of the along-track ( $\sigma_A$ ) and cross-track ( $\sigma_C$ ) deflection of the vertical errors may be expressed by the relationships:

$$\sigma_A = A_a d^{N_a}$$

$$\sigma_C = A_c d^{N_c}$$

where  $d$  is the distance traveled (in nautical miles) and the constants are functions of the GGI self generated noise PSD. The value range of these constants are shown in Table 4-5. The analysis described in this section was conducted using the  $25E^2$ /rad/sec GGI noise figure consistent with the Bell baseline GGI

#### 4.3.3.2.2 Analysis Methods and Assumptions

Two assumptions are made.

(1) Because of the isotropic nature of the gravity anomaly model, along-track and cross-track errors are considered to continue to accumulate in accordance with the error laws described in Section 4.3.3.2.1 even when the aircraft changes heading. The increments to the deflection of the vertical in the X direction (see Figure 4-8) is the statistical combination of the along-track errors when the aircraft is flying parallel to the X-axis with the cross-track error when the aircraft is flying in the Y direction. Similarly, the deflection of the vertical in the Y direction is the combination of the along-track errors when flying parallel to the Y-axis with the cross-track errors when flying parallel with the X-axis. This assumption further implies that the distance to be entered into the error expressions of the previous section are the sum of

TABLE 4-5  
ERROR COEFFICIENTS

GGI Noise PSD, $E^2/\text{rad/sec}$	<u>Aa</u>	<u>Na</u>	<u>Ac</u>	<u>Nc</u>
25	$3.37 \times 10^{-2}$	0.64	$1.49 \times 10^{-2}$	0.8
10	$1.05 \times 10^{-2}$	0.79	$5 \times 10^{-3}$	0.93
2	$1.34 \times 10^{-3}$	1.07	$7.1 \times 10^{-4}$	1.2

APPROXIMATIONS

$$Aa = 5.54 \times 10^{-4} P^{1.28}$$

$$Ac = 3.01 \times 10^{-4} P^{1.21}$$

$$Na = 1.183 P^{-y}, \quad y = 0.04 \log P + 0.135$$

$$Nc = 1.34 P^{-0.16}, \quad P = \text{Instrument Noise PSD, } E^2/\text{rad/sec}$$

the X,Y distances taken in the absolute sense; e.g., at the end of the Phase 1 traverse shown in Figure 4-8A, the X and Y distances traveled are each 20 grid units when the aircraft is back precisely at the start point.

(2) The deflection of the vertical errors, both along the along-track and the cross-track, are given by an expression of the form:

$$\epsilon = vd^n$$

where  $\epsilon$  is the error in milligals and  $v$  is a random variable which has a standard deviation equal to  $A_a$  or  $A_c$  as given in Table 4-5, for the along and cross-track errors, respectively. The variable  $d$  is the absolute distance traveled from the basic tie point, and the exponent,  $n$ , is also given in Table 4-5. A property assumed for the random variable,  $v$ , is that for an aircraft flying at a constant velocity, the correlation coefficient between values of  $v$  at distances  $d_1$  and  $d_2$  from the start point are given by

$$\rho = \frac{d_1}{d_2}, \quad d_2 > d_1$$

Two points are emphasized. First, this simple selection for the correlation coefficient  $\rho$  leads to conservative results as will be shown when the expression for residual errors after closure is discussed. Second, this should not be confused with spatial correlations of the gravity model. The gravity model and post-mission smoothing are embedded in the error curves of Figures 4-9 and 4-10. We are dealing here with the growth laws of the residual error after optimal use of the gravity model and post mission data smoothing.

#### 4.3.3.2.3 Relationships

This section lists results which follow from Section 4.3.3.2.2. The GGI self generated noise PSD is assumed to be  $25E^2/\text{rad/sec}$ . The definitions of the symbols used in the following expressions are listed in Table 4-6.

##### A. Open Traverse Errors

$$\sigma_{XD} = [4.63 \times 10^{-3} X^{1.28} + 1.29 \times 10^{-3} Y^{1.6}]^{\frac{1}{2}}$$

TABLE 4-6

## SYMBOL DEFINITION

SD	Standard Deviation
DOV	Deflection of the Vertical
$\sigma_{XD}$	SD of DOV in X direction, milligals
$\sigma_{YD}$	SD of DOV in Y direction, milligals
X	Absolute number of grid unit displacements from start to the survey point along the traverse in the X direction
Y	As X, except displacements in Y direction
$\eta_X, \eta_Y$	Errors in DOV at survey point; X, Y directions
$\Delta\eta_X, \Delta\eta_Y$	Correction to (X,Y) direction DOV's due to closure
$X_F, Y_F$	Same as X,Y except specifically designate tie-point to be used to correct other points at X,Y
$\eta_{XF}, \eta_{YF}$	Closure errors in DOV at tie-point
$\delta_1, \delta_2$	Estimates of DOV at survey point from two separate measurements
$\sigma_1, \sigma_2$	SD of errors associated with $\delta_1, \delta_2$
$\sigma_{1,2}$	SD of $\delta_{1,2}$
RSS	Root sum square; e.g., $\sqrt{\sigma_a^2 + \sigma_b^2}$
$\delta_{1,2}$	Combined estimate of DOV from separate measurements

$$\sigma_{YD} = [4.63 \times 10^{-3} Y^{1.28} + 1.29 \times 10^{-3} X^{1.6}]^{\frac{1}{2}}$$

## B. Closure Rules

(1) For  $\frac{1}{2} < \frac{X+Y}{X_F + Y_F} < 2$

$$\Delta \eta_X = v_{aF} X^{.64} + v_{CF} Y^{.8}$$

$$\Delta \eta_Y = v_{aF} Y^{.64} + v_{CF} X^{.8}$$

$$\text{Resulting } \sigma_{XD} = \sqrt{2} \sqrt{1-\rho} \times \text{open traverse } \sigma_{XD}$$

$$\text{Resulting } \sigma_{YD} = \sqrt{2} \sqrt{1-\rho} \times \text{open traverse } \sigma_{YD}$$

$$\rho = \frac{X+Y}{X_F + Y_F}, \quad (X+Y) < (X_F + Y_F)$$

$$= \frac{X_F + Y_F}{X+Y}, \quad (X+Y) > (X_F + Y_F)$$

$$v_{aF} = \frac{\eta_{YF} Y_F^{.8} - \eta_{XF} X_F^{.8}}{Y_F^{1.44} - X_F^{1.44}}$$

$$v_{CF} = \frac{\eta_{XF} Y_F^{.64} - \eta_{YF} X_F^{.64}}{Y_F^{1.44} - X_F^{1.44}}$$

(2) For all other  $(X+Y)$ ,  $(X_F + Y_F)$

No closure correction applied.  $\sigma_{XD}$ ,  $\sigma_{YD}$  remain as **for** the open traverse.

- (3) Comments: A consequence of the conservative assumptions is that no benefits to closure are carried back past the midpoints (1, 4). The error model postulated implies that traverse readings up to the midpoint are not benefited by closure correction of error buildup at the end point. The error estimates are conservative.



### C. Weighted Averaging

$$(1) \quad \delta_{1,2} = \frac{\sigma_2^2}{\sigma_1^2 + \sigma_2^2} \delta_1 + \frac{\sigma_1^2}{\sigma_1^2 + \sigma_2^2} \delta_2$$
$$\sigma_{1,2} = \frac{\sigma_1 \sigma_2}{\sqrt{\sigma_1^2 + \sigma_2^2}}$$

- (2) Comments: From the two perimeter runs, two estimates for each of the X deflection of the vertical and Y deflection of the vertical are obtained which are combined using expression (1) above. The interior points are closed by the four "adjacent perimeter" points (see Section 4.3.3.2.4). These are combined by repeated application of Equation (1) above.

#### 4.3.3.2.4 Procedure

- (1) Fly the survey traverse as shown in Figure 4-8.
- (2) Using post-mission analyses, compute the deflections of the vertical (DOV) of the perimeter points using the Initial Perimeter and Mission Conclusion Perimeter Traverses (Figures 4-8A and 4-8C, respectively). The closure error of point (1,1), i.e., the Basic Reference Tie-Point, is used at the end of Phase 1 to correct the Phase 1 perimeter deflection of the vertical estimates. The closure rules are discussed in Section 4.3.3.2.3. At the end of Phase 3, the data is reinitialized in the post-mission smoothing to the tie-point value by the second closure. A second set of independent perimeter deflections of the vertical are computed from the data of the Phase 4 perimeter run. This second set is corrected by the closure error determined by the third closure.
- (3) Treating the two sets of perimeter deflections of the vertical as independent, obtain the final estimates by weighted averaging.
- (4) Compute deflections of the vertical for interior points as traversed in Phases 2 and 3. Since these phases begin and end at the tie-point (1,1), deflection of the vertical estimates are again adjusted by the closure rules. For each interior point, there now are two sets of estimated deflections in the X and Y directions corresponding to the lateral and longitudinal grid traverses.

(5) For each set of the deflections of the vertical connected with each interior point, perform forward and reverse closures to the adjacently traversed perimeter points, e.g., (a) the deflection of the vertical estimate of point (9,5) is forward closed using tie-point (10,5) and reversed closed using tie-point (1,5) from the lateral grid traverse, and (b) forward closed using tie-point (9,1) and reverse closed using tie-point (9,11) from the longitudinal traverse. For the deflections of the vertical in the X and Y directions, there are now four estimates each. Each of these estimates is based on the closure error of the Phase 2 and 3 traverses over the perimeter points as compared with the perimeter point estimates from Step 3 above.

(6) Calculate weighted averages of the four estimated values for both the X and Y deflections of the vertical.

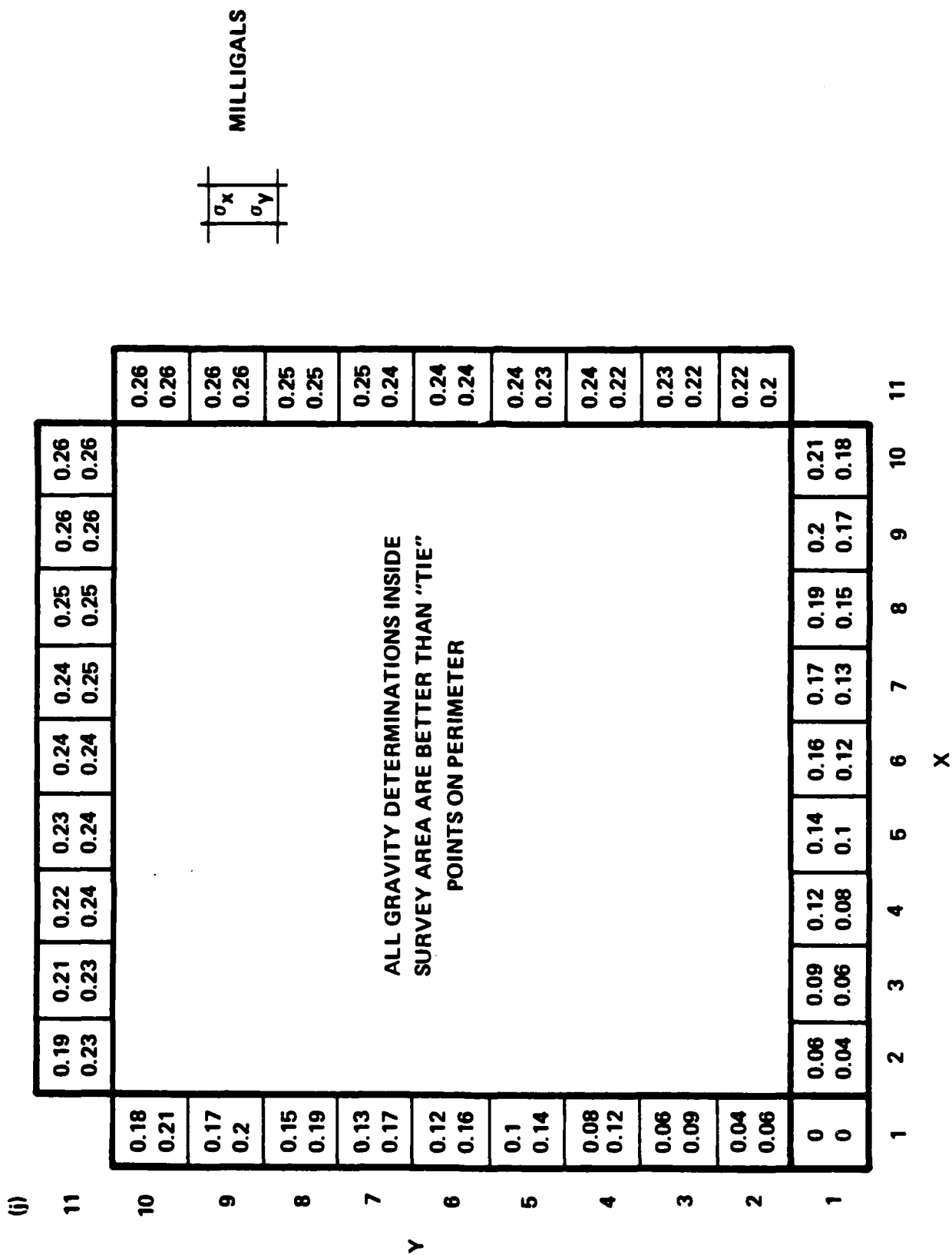
(7) An estimate of the standard deviation of the absolute error is obtained by the root sum square of the standard deviation of the error of perimeter points from Step 2 with the standard deviation of the error transference from perimeter tie-point to the survey point. Four estimates result, which are then combined by weighted averaging.

#### 4.3.3.2.5 Results

The largest survey errors occur at the diagonally opposite perimeter points from the start point (the reference point). The magnitude of these errors is less than 0.26 milligals, or the equivalent of 0.05 arc sec deflection of the vertical, in orthogonal directions. If the detailed analysis in progress supports this report, which is expected, it is concluded that reducing the GGI self generated noise below  $25E^2/\text{rad/sec}$  would not be justified for missions of this length since other error sources now become dominant. However, noise reduction programs are ongoing to satisfy any potential future application. Figure 4-11 tabulates the perimeter point errors so obtained.

The following demonstration based on the "worst case" interior point shows that no interior point can exceed the perimeter point errors using the procedures described. First, determine the worst case point. The length of the Phase 2 and 3 traverse is 339 grid units. In Section 4.3.3.2.3, it was stated that the maximum

FIGURE 4-11. STANDARD DEVIATION OF PERIMETER TIE-POINTS



error standard deviation after closure correction occurs at the trajectory midpoint and that the value is then the same as for the open loop traverse. The midpoint is reached in 170 grid units. This is point (6,5) which is reached near the end of Phase 2. This point is also in the center of the grid and approximately equally spaced from its perimeter tie-points (1,5), (11,5), (6,11), (6,1).

Since this is the worst case interior point, it is sufficient to show that its error is less than the maximum error of the worst perimeter point. To illustrate this point, determine the error standard deviation of the deflection of the vertical in the X direction of point (6,5) following the sequence outlined in Section 4.3.3.2.1 using the relationships of Section 4.3.3.2.3. The error standard deviation of the deflection of the vertical in the Y direction will be essentially identical.

(1) Open Traverse Error

For point (6,5) Phase 2 crossing, X = 116, Y = 54

$$\sigma_{XD} = [4.63 \times 10^{-3} X^{1.28} + 1.29 \times 10^{-3} Y^{1.6}]^{\frac{1}{2}} = 1.67$$

(2) Closure to Peripheral Tie-Points

a. Tie-point (11,5) Phase 2 crossing: X = 111, Y = 54

$$\rho = \frac{165}{170} = 0.97$$

$$\text{Relative error after closure} = \sqrt{2} \sqrt{1-\rho} \sigma_{XD} = 0.41$$

$$\text{Absolute error SD after closure} = \sqrt{0.24^2 + 0.41^2} = 0.48$$

where 0.24 is the error SD of tie point (11,5)

b. Tie-point (1,5), Phase 2 crossing: X = 121, Y = 54

$$\rho = \frac{170}{175} = 0.97$$

$$\text{Relative error SD after closure} = \sqrt{2} \sqrt{1-\rho} \sigma_{XD} = 0.41$$

$$\text{Absolute error SD after closure} = \sqrt{0.41^2 + 0.1^2} = 0.42$$

where 0.1 is the error SD of tie-point (1,5)

- c. Tie-point (6,11) Phase 3 crossing: X = 140, Y = 64  
 Point (6,5), Phase 3 crossing: X = 140, Y = 70

$$\rho = \frac{204}{210} = 0.97$$

$$\text{Relative error after closure} = \sqrt{2} \sqrt{1-\rho} \sigma_{XD} = 0.41$$

$$\text{Absolute error SD after closure} = \sqrt{0.41^2 + 0.24^2} = 0.48$$

where 0.24 is the error SD of tie-point (6,11)

- d. Tie-point (6,1, Phase 3 Crossing: X = 140, Y = 79

$$\rho = \frac{210}{214} = 0.98$$

$$\text{Relative error SD after closure} = \sqrt{2} \sqrt{1-\rho} \sigma_{XD} = 0.33$$

$$\text{Absolute error SD after closure} = \sqrt{0.33^2 + 0.16^2} = 0.37$$

where 0.16 is the error SD of tie-point (6,1)

### (3) Weighted Averaging

The four estimates have respective error standard deviations as follows:  $\sigma_1 = 0.48$ ,  $\sigma_2 = 0.42$ ,  $\sigma_3 = 0.48$ ,  $\sigma_4 = 0.37$ . After weighted averaging, the estimated error is given by the relationships of 4.3.3.2.3c.

$$\begin{aligned} \sigma &= \frac{\sigma_1 \sigma_2 \sigma_3 \sigma_4}{[(\sigma_1 \sigma_2 \sigma_3)^2 + (\sigma_1 \sigma_2 \sigma_4)^2 + (\sigma_1 \sigma_3 \sigma_4)^2 + (\sigma_2 \sigma_3 \sigma_4)^2]^{\frac{1}{4}}} \\ &= 0.21 \text{ milligals (standard deviations)} \end{aligned}$$

Note that this is less than the worst case perimeter point. The improvement results from the benefits of closure and weighted averaging to four tie-points.

#### 4.3.3.2.6 Conclusions and Commentary, Airborne Surveyor

A. The requirements for the transfer of the deflection of the vertical with errors of less than 1 milligal is easily achieved for the traverses postulated with a GGI of  $25E^2/\text{rad/sec}$  noise level. The instrument noise expected in the near future is projected to be  $10E^2/\text{rad/sec}$  and no restriction on traverse configuration need be imposed.

B. With the current GGI, simple traverses can be devised which enable survey error reductions by establishing secondary tie-points of high accuracy. These traverses can be implemented by straightforward flight pattern algorithms.

C. The option for further error reduction by repeated measurements can be easily implemented; e.g., the model traverse can be expanded to any number of perimeter runs - a simple continuous circling of the area to be mapped.

D. Staying strictly with the form of the four phase traverse described, the maximum error in transfer of the deflection of the vertical can be stated for any size survey. The points of maximum error are the perimeter points diagonally opposite the starting tie-point. For a grid with  $n$  units per side, these points are displaced by  $x = y = n$  grid units. For grid spacings of 3 NM, the maximum errors are:

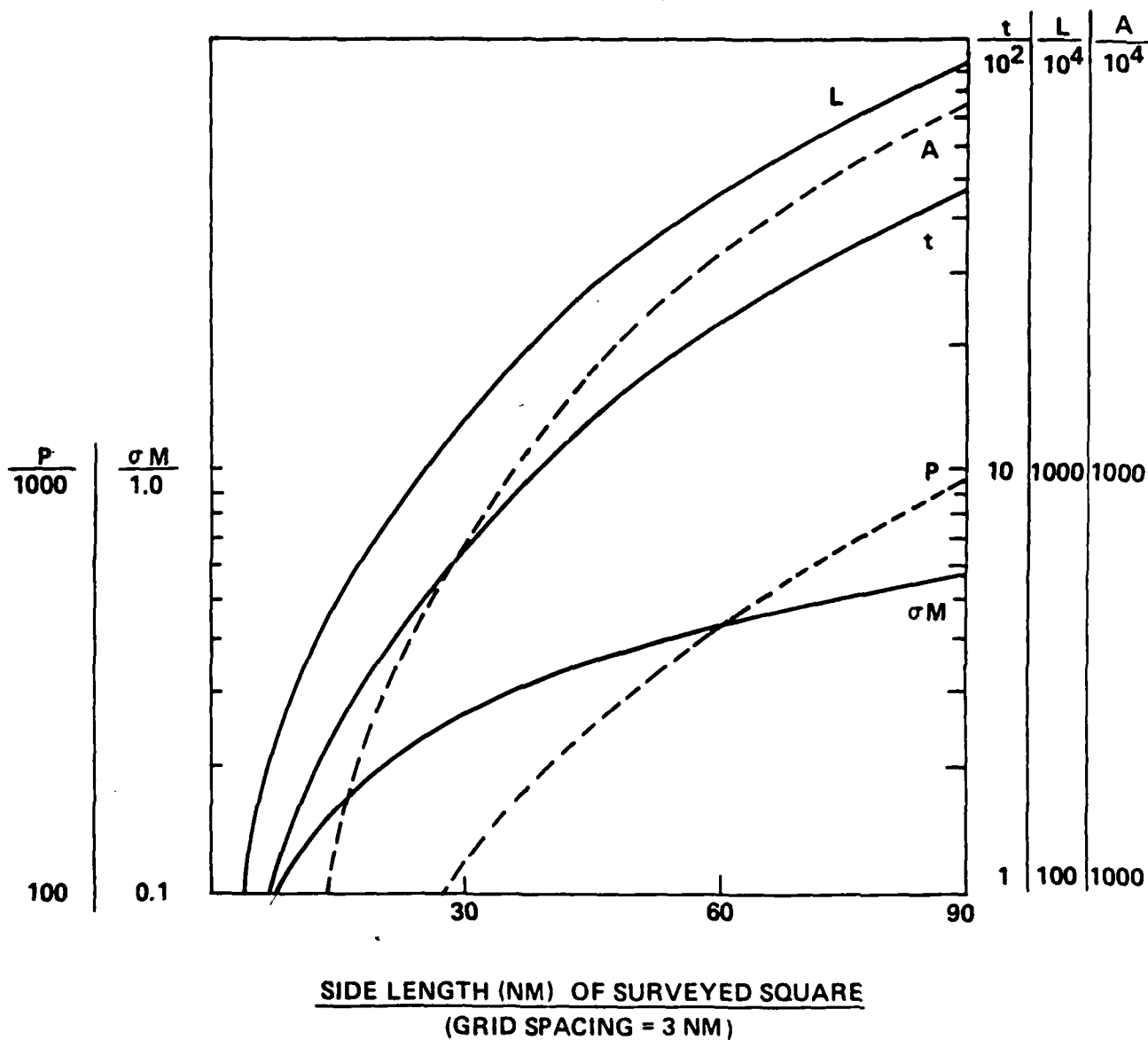
$$\begin{aligned}\sigma &= [4.63 \times 10^{-3} x^{1.28} + 1.29 \times 10^{-3} y^{1.6}]^{\frac{1}{2}} \\ &= 0.036 [3.59n^{1.28} + n^{1.6}]^{\frac{1}{2}}\end{aligned}$$

where  $\sigma = \sigma_{XD}$  (Phase 1) =  $\sigma_{YD}$  (Phase 1) =  $\sigma_{XD}$  (Phase 2) =  $\sigma_{YD}$  (Phase 2). Combining the  $\sigma_{XD}$ 's and  $\sigma_{YD}$ 's is simply division of  $\sqrt{2}$ , yielding, for the two deflections of the vertical:

$$\sigma_M = 2.55 \times 10^{-2} [3.59n^{1.28} + n^{1.6}]^{\frac{1}{2}}$$

The mapped area is  $A = (n-1)^2 \ell^2$  where  $\ell$  is the grid spacing. The path length is  $L = \ell(3n^2 + 15.28n + 14.57)$ . The number of added survey points is  $P = n(n+2)$ . These relationships are plotted in Figure 4-12. They are plotted as continuous functions though the side lengths of the surveyed square must be discrete, even multiples of the grid spacing, and the side lengths more than 12 miles (5x5 grid), in order to maintain the form of the selected traverse.

FIGURE 4-12. SUMMARY OF RESULTS FOR  $25E^2/\text{rad/sec}$  GGI



- $\sigma_M$  MAX ERROR STANDARD DEVIATION - MILLIGALS
- P NUMBER OF SURVEY PRINTS MAPPED
- t MAPPING TIME - HOURS AT 200 KNOTS
- L TRAVERSE LENGTH - NM
- A AREA MAPPED - NM<sup>2</sup>

The time shown is the actual mapping time which is exclusive of the time required for the aircraft to climb to altitude, set up, and to return to base. An 11x11 grid, the size analyzed, would require 7 hours of mapping time and a 13x13 grid, the next largest size which conforms with the selected traverse, would require 9.4 hours. Because of aircraft endurance, with the assumed flight conditions and grid spacing, the grid analyzed is the largest one practical. These conclusions are based on the dense grid (close survey point spacing) analyzed. Section E (following), discusses SPARS grids which enable consideration of larger areas.

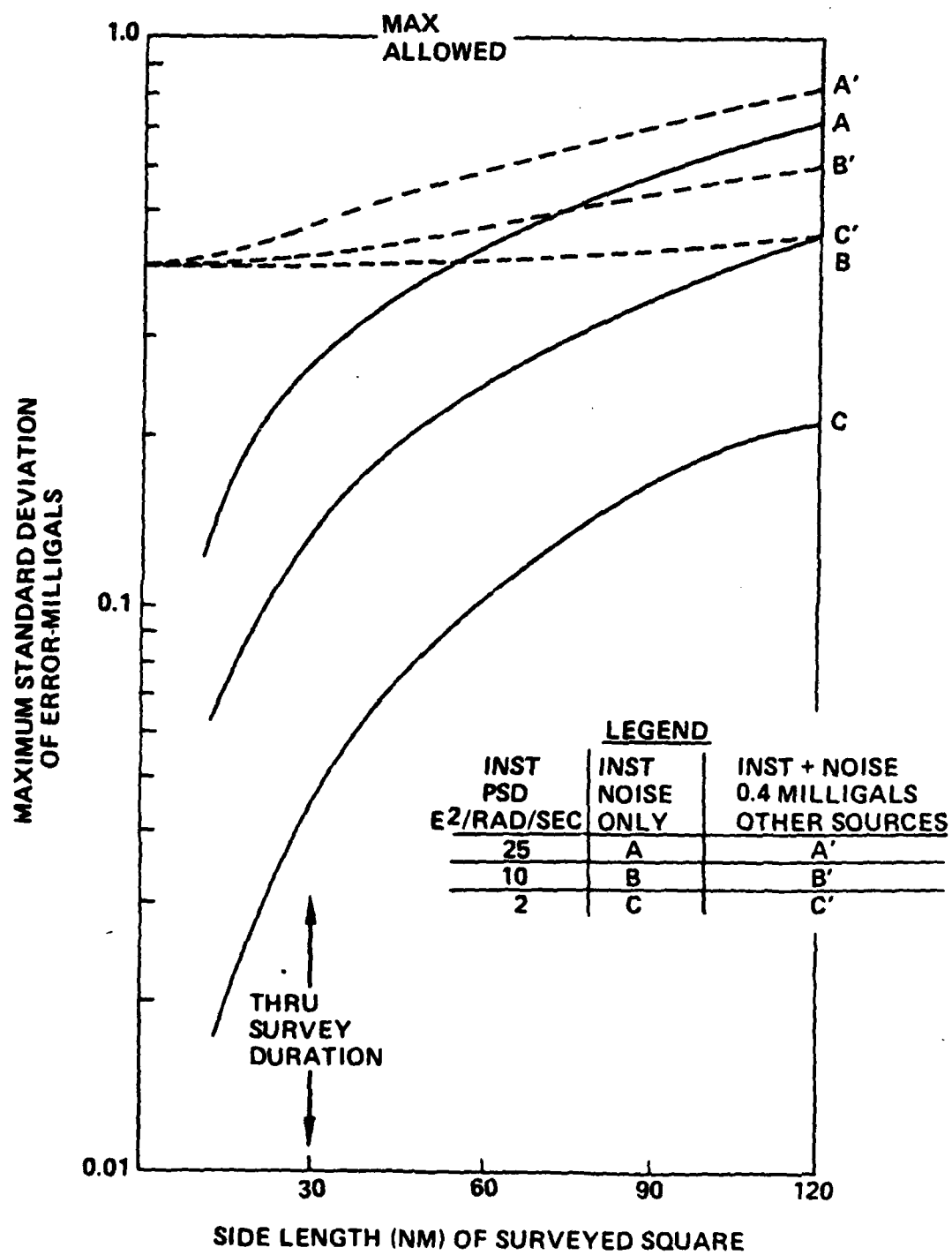
With the dense grid, the standard deviation of the deflection of the vertical errors due to only instrument noise is never the limiting factor on mission length. Note that after 47 hours of hypothetical non stop survey flying, the standard deviation of the deflection of the vertical due to instrument noise is 0.58 milligals (0.12 arc sec). Of course, other error sources must also be considered besides GGI self noise for a complete assessment.

E. Figure 4-13 compares the standard deviation of the deflection of the vertical transference errors for the instrument self generated noise PSD's of  $25E^2/\text{rad/sec}$ ,  $10E^2/\text{rad/sec}$ ,  $2E^2/\text{rad/sec}$ . Two comparisons are shown. First, the standard deviations due only to GGI self noise and, second, the standard deviations due to instruments combined with assumed additional errors from other sources such as navigation errors. The assumed additional errors are taken to be uncorrelated and with standard deviations of 0.4 milligals.

For the dense grid, the other error sources dominate the total error for all noise levels. For the 7 hour survey time, the largest considered practical, the error spread of the standard deviation is between 0.4 and 0.48 between the 2 and  $25E^2/\text{rad/sec}$  instruments. For practical time duration missions, the error in deflection of the vertical will not exceed 0.5 milligals RMS or half the maximum allowed even when other noise sources are considered. The expenditure of resources to reduce the GGI's noise level from  $25E^2/\text{rad/sec}$  would be unjustified for this sized grid utilizing the peripheral tie point concept.



FIGURE 4-13. COMPARISON OF THREE GGI NOISE LEVELS



F. Figure 4-14 shows the standard deviation of the maximum error as a function of GGI self generated noise with surveyed area side lengths as a parameter. The approximations listed in Table 4.5 are used to extend these results beyond the three cases simulated (see Section 4.3.3). For 1 milligal error, ignoring other error sources, the gravity gradiometer instrument can be degraded as follows:

<u>Traverse Side Length (NM)</u>	<u>Allowable GGI Self-Noise (<math>E^2</math>/rad/sec)</u>
120	45
90	60
60	85
40 (the dense grid)	130

The maximum error is a function of the length of the survey areas side length while the duration of flight time is a function of side length and the grid spacing. The larger areas can be accommodated by opening the spacing between survey points to establish a less dense grid. Modified traverse patterns would be considered to accommodate these cases.

#### 4.4 Vehicle and Gimbal Self Gradients

##### 4.4.1 Introduction

A gradiometry error source which is independent of gradiometer design is the presence of very near external masses which are present because of the gradiometer installation. Gradients caused by the mass of elements physically located within the IGMS platform or by the vehicle's structure and contents are referred to as self-generated gradients. These errors must be removed (compensated for) during system operation to the extent necessary to meet performance requirements. BAT has successfully solved this problem for the GSS ADM system now in test aboard the USNS Vanguard.

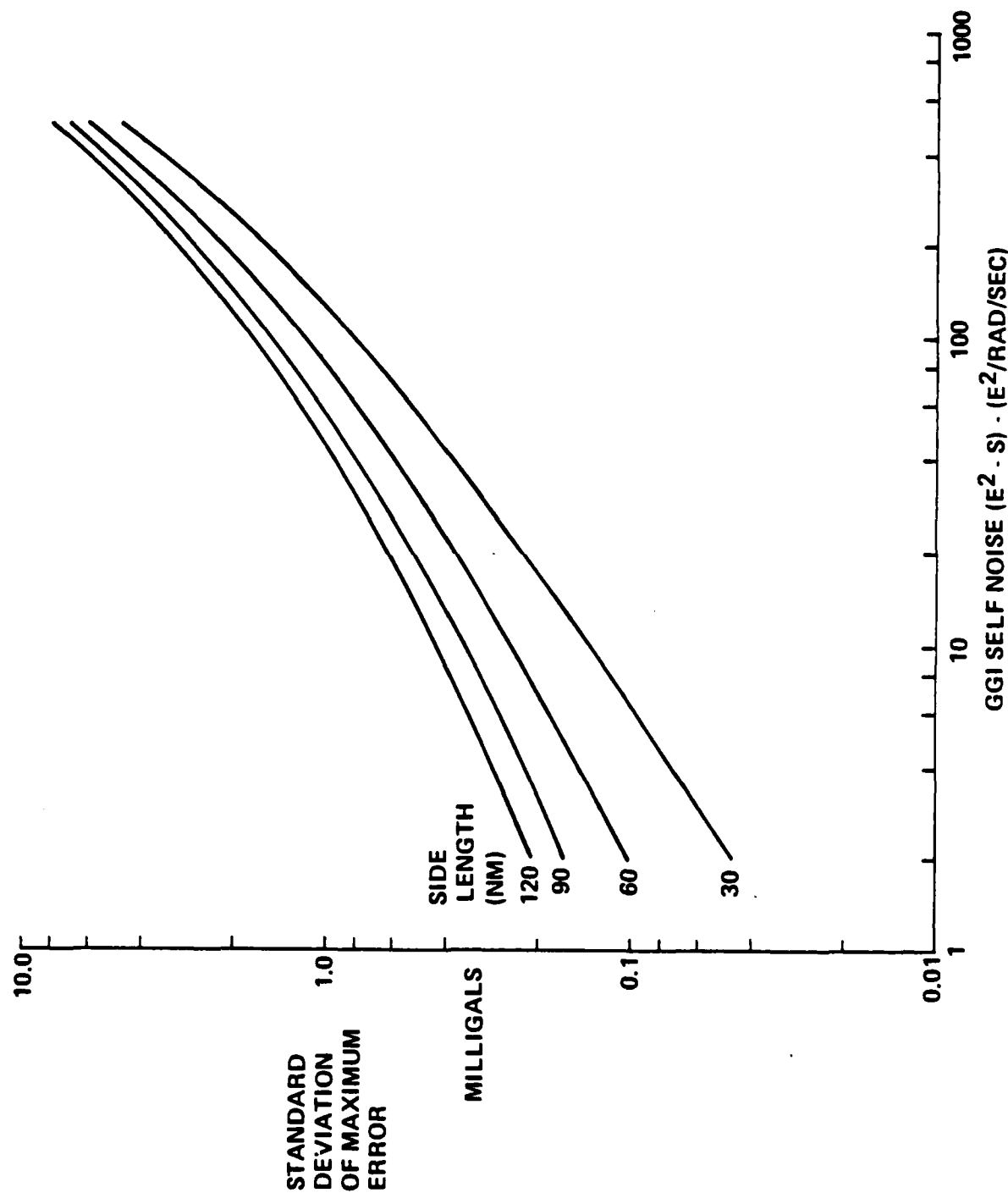
To illustrate the self gradient problem and its solution, consider the following structures surrounding the GGI instrument cluster.

- (1) Pitch gimbal and associated torquer, synchro, bearings, etc.
- (2) Roll gimbal and associated torquer, synchro, bearings, etc.
- (3) Instrument binnacle and mass structure of the vehicle

The first two of these, although fixed as to form and mass, produce instrument output variation due to their attitude variations relative to the stabilized instrument cluster. Structure (1) varies in azimuth with respect to the instrument cluster, while (2) varies in both azimuth and pitch. The third and fourth

FIGURE 4-14

GRAVITY SURVEY ACCURACY AS FUNCTION OF SURVEY AREA AND GGI NOISE



The self gradient compensation functional form is then:

$$\begin{aligned}
 y_c = & \sum_{i_1=1}^9 \sum_{j_1=1}^6 \sum_{k_1=1}^6 \alpha_{i_1 j_1 k_1} \theta^{k_1-1} \phi^{j_1-1} \cos(i_1-1)\psi \\
 & + \sum_{i_2=1}^9 \sum_{j_2=1}^6 \sum_{k_2=1}^6 \beta_{i_2 j_2 k_2} \theta^{k_2-1} \phi^{j_2-1} \sin i_2 \psi + f(\delta W)
 \end{aligned} \tag{1}$$

Note that one of these compensation terms is required for each of the six GGI outputs, and that  $f(\delta W)$  is an additional compensation term which tracks slowly varying changes in the vehicle's second order tensor.

The purpose of the calibration scheme is to fix the operational parameters  $\alpha_{i_1 j_1 k_1}$  and  $\beta_{i_1 j_1 k_1}$ .

Because the three mass structures are in close proximity to the GGI sensing units, the finite distance over which the field is measured (from which the gradient at a point is inferred) and the physical displacement between each of the three sensors has to be accounted for. Therefore, the individual accelerometer outputs are considered in the analysis.

Considering the inner element to be fixed, the three mass structures rotate about axes passing through the symmetric gimbal center. Working in a coordinate system fixed in the  $i^{\text{th}}$  mass structure with origin at the gimbal center an accelerometer output can be written as a Taylor series expansion about the gimbal center. The elements of the tensors in the mass fixed coordinate set constitute a list of constant numbers that describe the structure sufficiently to calculate the accelerometer and hence the GGI outputs.

The first stage in the analysis then is to derive the matrix  $H(\theta, \phi, \dots)$  where:

$$\underline{y} = H(\theta, \phi, \dots) \cdot \underline{\omega}^L \tag{2}$$

$\underline{\omega}^L$  is vector containing the independent elements of the tensors appearing in the Taylor series (truncated after a suitable number of terms) taking into account symmetry and the Laplacian constraints.

$\underline{y}$  is the GGI output vector.

The elements of the vector  $\omega^L$  constitute the minimum parameterization of the estimation problem. The essence of the calibration scheme is to identify as much of  $\omega^L$  as possible by exercising the gimbals and filtering the GGI output.

In order to exercise the gimbals, two types of inner element motion are considered:

- Keeping the inner element z axis and the local g vector coincident by carouseling about z.
- Keeping the angle between the inner element z axis and the local g vector constant by causing the z axis to describe a cone about the local g vector.

The calibration procedure proceeds in three stages now described.

#### 1. Laboratory Calibration

For the laboratory calibration, the GGI's are mounted in the platform and on a Scorsby two axis angular motion test table. The inner element is then held at a number of positions obtained by undergoing the motions described above. At each position, the Scorsby table tilt and azimuth gimbals are exercised, thus indirectly causing the platform gimbals to be exercised.

In the laboratory case, a far greater number of platform gimbal positions can be used because of the extra degrees of freedom afforded by the Scorsby gimbals. However, because the Scorsby is a relatively massive nearly object, the tensor elements describing it have to be identified as well as the gimbals. Hence, in the laboratory a total of five mass structures have to be identified.

After the laboratory calibration, the two inner gimbals are mainly identified. The binnacle is bolted to the Scorsby azimuth structure and this composite structure is also mainly identified. The tensor elements describing the remaining Scorsby structures and local earth are discarded.

#### 2. Pre-Mission Vehicle Self Gradient Calibration

The purpose of a pre-mission vehicle self gradient calibration is to identify as much of the vehicle self gradient effects as possible. The platform gimbals can only be exercised by the carouseling and coning motions as described above. The number of parameters to be identified is much fewer, however, as the

Taylor series for the third mass structure is taken to fewer terms than for the two gimbals. Also, the tensor corresponding to the third mass structure is partially identified. At the completion of the premission vehicle self gradient calibration the third and higher order tensor corresponding to the third mass structure are mainly identified. The second order tensor corresponding to the third mass structure is corrupted by the earth local field.

This final part of the calibration procedure is to correct the second order tensor corresponding to structure three as well as any remaining higher order tensor elements. To do this the gimbals are exercised by moving the vehicle itself. With aircraft this would be done by a towing vehicle such that the aircraft assumes various headings.

The end result of the calibration procedure is an estimate of  $\underline{\omega}^L$ ,  $\underline{\hat{\omega}}^L$ . By computing the matrix  $H(\theta, \phi, \psi)$  and using  $\underline{\hat{\omega}}^L$ , an estimate of the GGI output resulting from the gimbal, binnacle and vehicle fields can be calculated. In theory this estimate could be used as the compensation. In practice this cannot be done as the matrix  $H(\theta, \phi, \psi)$  takes excessive CPU time to compute. The tensor estimate  $\underline{\hat{\omega}}^L$  and the matrix  $H(\theta, \phi, \psi)$  is, in fact, used to generate a large number of output estimates. A three-dimensional surface fit is then carried out over these data points to fix the parameters required by the operational program,  $\alpha_{i_1 j_1 k_1}$  and  $\beta_{i_2 j_2 k_2}$ .

#### Practical Details and Problem Areas

There are some fundamental problem areas in addition to a number of practical problems that were identified as a result of carrying out statistical and Monte Carlo simulations as well as mass modeling. These now are listed together with their solutions where appropriate.

1. When the orientation of a GGI is changed with respect to the local g vector, it essentially becomes a different instrument in as much as the biases, ramps, and exponentials present in the output will undergo a jump change. To account for this in the filter, the diagonal elements of the covariance matrix corresponding to these noise states are incremented by an amount reflecting statistically the magnitude of the change expected.

2. The calibration scheme assumes that only the gravitational fields are measured by the GGI. Any magnetic or pressure sensitivity effects (for example) causing changes in the outputs will corrupt the data as they are not modeled. The projected GGI design minimizes this effect and it is not expected to be significant.

3. There will exist strong correlations between elements of  $\hat{\omega}^L$  (equivalent to unobservability) which can never be broken down by exercising the gimbals. These cause no direct problem as the elements will not become observable during a mission. This implies that there is an infinite number of vectors  $\hat{\omega}^L$  which will serve our purpose. There are however some indirect implications of these correlations. For example, when carrying forward the estimate  $\hat{\omega}^L$  from the laboratory to the vehicle, the covariance matrix has to be carried forward also. Only the states corresponding to instrument noise are then initialized.

4. During the premission vehicle self gradient calibration, the field due to any nearby structures will be significant. Mass modeling studies indicate that if the vehicle is located as far away from any nearby structures as possible, this field will only affect the second order tensor for structure three which is corrupted already by the local earth field. With the described calibration technique, the contributions of structures near the vehicle to the second order tensor is removed. These contributions are accounted for in the filter by incrementing the appropriate diagonal elements of the covariance matrix.

5. During the initial part of the premission vehicle self-gradient calibration where the inner element is simply carouselled any symmetric vehicle structures will appear as a GGI bias. When the inner element is tilted with respect to the local  $g$  vector, the GGI bias changes hence the filter will detect a new symmetric structure and bias as it cannot distinguish between the two. Hence, at the end of the premission vehicle self gradient calibration,  $\hat{\omega}^L$  will be in error by the addition of a symmetric structure. It turns out that relatively few numbers are required to specify symmetric structure tensors implying that  $\hat{\omega}^L$  can be corrected by adjusting only a few elements.

6. The GGI output is operated on a Butterworth filter, implemented in a microprocessor sampling at 32 Hz. The DOC samples the microprocessor every two seconds. In order to match the filtered GGI outputs, the self gradient compensation function operates on two second averaged gimbal angles and the compensation signal passed through an equivalent Butterworth filter implemented in the DOC.

7. Implicit in this analysis is the assumption that the vehicle angular motions have a significantly lower frequency than that of the GGI wheel speed, i.e., the self gradient signal is assumed to be completely contained in the  $\sin 2st$  and  $\cos 2st$  spectrums. In a land vehicle or aircraft application, this would not be the case implying that the self gradient compensation would be a function of wheel angle,  $\Omega t$ , as well as gimbal angles. The additional compensation to account for this effect is readily accomplished by post-mission computation from the recorded data with a minor increase in the computational load.



## 5.0 MISSION REQUIREMENTS - ENVIRONMENTAL DISTURBANCES

### 5.1 Angular Vehicle Motion

The GSS gyro stabilized platform maintains the three GGI's, mounted at the umbrella angle, in the north, east, vertical coordinate reference system. Initially, "jitter" induced GGI noise from the platform stabilization system was of major concern. Jitter is the square of angular rate and appears as an anomalous gradient component. A comprehensive platform analysis and investigation has been conducted over the last three years with the result that platform induced jitter, even under severe angular inputs of  $24^{\circ}$  peak-to-peak with a ten second period, produce negligible jitter error. This was achieved by using low stiction platform components, dry tuned gyros and high gain platform stabilization loops. Frequency response, as defined by  $90^{\circ}$  phase shift, is above 23 Hz for the azimuth, pitch and roll gimbal servos.

For monitoring purposes, the gyro rate signals have been instrumented to measure jitter and can be used to correct the measured gradient signals. This has not been found necessary for conditions on the Vanguard even though peak-to-peak roll angles of over  $30^{\circ}$  have been experienced.

### 5.2 Linear Vehicle Accelerations

The rotating accelerometer gravity gradiometer exhibits sensitivities in response to accelerations at the three first harmonics of spin speed. The sensitivities to steady state and broad band accelerations are negligible until structural GGI and platform resonances produce jitter. The structural resonances are well above 60 Hz and the platform vibration isolation system effectively prevents these from being excited.

The sensitivities to acceleration inputs at the first three harmonics stem from residual even order acceleration error coefficients and residual misalignment of the net accelerometer input axes into the spin axis. Active or passive compensation reduce these acceleration sensitivities to under 5E per mg. For the Navy application, this contributes negligible GGI noise in response to the submarine vibration environment.

The US Navy Ship Vanguard exhibits vibration levels at the critical frequencies many order of magnitudes higher than specified for the submarine. An investigation has been initiated to explore how well these acceleration sensitivities can be minimized using a low frequency platform perturbation technique. Indications are that sensitivities of under 0.1 E/mg will be attainable. Using this sensitivity as a guideline for the seven acceleration sensitivities in conjunction with an acceleration budget of  $3E^2/\text{rad/sec}$ , the allowable acceleration environment aboard the aircraft or land vehicle at the critical frequencies can be defined as follows:

$$\phi_{\text{GGI Noise}} = \frac{7}{2} \times (K_{a\text{GGI}})^2 \times \phi_a$$

where

$\phi_{\text{GGI}_a}$  = The GGI acceleration induced noise power spectrum ( $3E^2/\text{rad/sec}$ )

$K_{a\text{GGI}}$  = The GGI acceleration sensitivity (0.1E/mg)

$\phi_a$  = The acceleration power spectrum of the vehicle at the critical frequencies ( $1/4$  to  $3/4$  Hz)

Statistically, the acceleration disturbances may affect either output channel of the GGI equally and, hence, the factor of 2 in the denominator.

$$t_{in} = \frac{\phi_{\text{GGI Noise}}}{3.5(K_{a\text{GGI}})}$$

$$t_a \text{ permissible} = 85(\text{mg})^2/\text{rad/sec} = 8.5 \times 10^{-5} g^2/\text{rad/sec}$$

The allowable acceleration power spectral density (between  $1/4$  and  $3/4$  Hz) is approximately four orders of magnitude larger than that of a submarine and should not be exceeded on almost any aircraft and land vehicle under reasonable flight or road conditions. In the frequency region about  $1/4$  Hz, this magnitude of acceleration input would cause one-sigma displacements of 4.8 cm with peaks of 15 cm. Displacements of this magnitude have not been observed or sensed by passenger flight experience on commercial airliners in nonturbulent flight. Further

investigations with respect to aircraft and land vehicle acceleration environments will be conducted in the future.

### 5.3 Linear and Angular Vehicle Vibration Environment

A linear and angular vibration isolation system has been designed and fabricated by the MRAD Corporation of Boston to Bell specifications. The resonant frequencies of the vibration isolation system vary between 11 and 17 Hz with Q's of under three in all six modes. Avoiding excitation of structural gimbal and GGI resonance from vehicle vibration is the principal purpose of the isolation system. Test on the NS Vanguard has verified the effectiveness of the linear and angular vibration isolation system.

### 5.4 Ambient Temperature Environment

The GGI's are protected from the vehicle temperature environment by the platform temperature control system which is being maintained inside the platform enclosure to better than  $0.1^{\circ}\text{F}$  for external variations of  $10^{\circ}\text{F}$ . The low GGI temperature sensitivity of much less than  $1\text{E per }^{\circ}\text{F}$  make temperature variations a negligible error contributor.

### 5.5 Humidity Environment

No humidity sensitivity has been identified over RH changes of 10%.

### 5.6 Barometric Pressure Environment

At present the GGI's are pressure corrected using a recording barometer (furnished with the system) and measured pressure sensitivities for each instrument. Investigations and experiments are in progress to reduce the less than  $25\text{E/inch}$  pressure sensitivities. The Model VII accelerometer casing is a prime suspect for this pressure sensitivity.

### 5.7 Magnetic Environment

The magnetic GGI sensitivity of under  $0.5\text{E/Oe}$  is a negligible error contribution from this source.

## 6.0 DESIGN MODIFICATIONS REQUIREMENTS

### 6.1 General

The Integrated Gravity Mapping System (IGMS) will be a self contained "turn-key" package and will, for cost effectiveness and proven performance, be based on the evolving hardware and software concepts of the Advanced Development Model Gravity Sensors System (GSS ADM). The principal changes between the GSS ADM system and the IGMS are:

- (a) The addition of an Inertial Navigation System
- (b) The selection of new digital computer
- (c) The redesign of the platform enclosure (binnacle) and its associated cooling system, and
- (d) The inclusion of a gravity meter

The following paragraphs outline the modifications required to the existing GSS ADM system concepts to meet the proposed IGMS application. Section 7.0 addresses the design tradeoffs implicit in these modifications.

### 6.2 Inertial Navigation System

The IGMS configuration will be a self-contained "turn-key" package. This requires the selection of an Inertial Navigation System (INS) to provide reference vehicle attitude and velocity data. The GSS ADM uses the ships Inertial Navigation System for this function. Decisions that had to be made in the selection of an INS for the IGMS application involved consideration of:

- Use of a Dedicated INS versus the Vehicle INS
- Performance Requirements
- Reliability
- Cost
- Commonality among all IGMS Applications
- Vibration Isolation
- Cooling

### 6.3 Electronic Cabinets

The IGMS will retain the Electronic Cabinets designed for the GSS ADM, the most cost effective approach. The cabinets are described in Section 3.0. This design calls for two electronic cabinets, one to control the GGI's, the other to control the platform and interface with the computer. These cabinets house all the electronic circuits and components which are not housed in the GGI's or on the platform. These cabinets will require only minimal changes to support the addition of a gravimeter on the platform. These changes will include:

- The inclusion of the gravimeter related control electronics
- The additional gravimeter to computer interface
- Additional power supply requirements

### 6.4 Dedicated Operational Computer

#### 6.4.1 Hardware

The dedicated computer used in the GSS ADM system is a government furnished, commercially available, Digital Equipment Corporation VAX-11/780. This computer was subsequently modified to suit the environment anticipated in the Naval Test Vehicle. A more rugged computer is desirable for the IGMS application. For this selection, the following requirements (among others) are addressed in Section 7.0.

- Computer Language (the GSS ADM computer is programmed in PASCAL)
- Memory Requirements (considering the real time requirements)
- Cooling Requirements
- Peripherals Required
  - Memory Expansion Cabinet
  - Disc Drive
  - Tape Drive(s)
  - Operator Terminal/Printer
- Environmental Requirements Anticipated
  - Ground Mobile Application
  - Airborne Application

#### 6.4.2 Software

The IGMS differs from the GSS ADM system in the following areas:

- Inertial Navigation System
- Dedicated Operational Computer
- Gravimeter

This requires that some of the software already designed and developed for the GSS ADM system be modified in those areas related to these differences.

#### 6.4.3 Other Computer Requirements for the IGMS Application

The development and operation of the IGMS system will require three distinct computer related activities:

- Software Development
- IGMS Dedicated Operational Program
- Post-Mission Data Reduction

The software development requirement and the post-mission data reduction requirement can both be satisfied by the same computer since computer usage for these tasks arises at different stages of the program. The computer used for these applications need not be of the same type but similarity in requirements favor commonality. These similarities are:

##### a) Software Development System

- Language Compatibility
- Memory Requirements
- Peripherals Required
  - Disc Drive(s)
  - Tape Drive(s)
  - Terminals
  - Printer(s)

##### b) Post-Mission Data Reduction System

- Language
- Memory
- Software Definition
- Software Development

These requirements, together with the advantages of commonality, will be addressed in Section 7.0, outlining the procedure for selecting the best computer type to meet all the requirements.

#### 6.5 Binnacle/Platform

The Binnacle and Platform subsystem provides the inertially stabilized and thermally controlled instrument bed required to house the inertial instruments. These inertial instruments are the Bell gravity gradiometer instruments (the GGI's), the two gyros and two accelerometers required for platform stabilization and the gravimeter. The inertial instruments planned for the IGMS are the same as those used for the GSS ADM. The new requirements for the IGMS are:

- Installation of the Gravimeter
- The Cooling Technique for the Binnacle
- The Vibration Isolation System Mounting

#### 6.6 Gravimeter

As already stated, a difference between the GSS ADM and the IGMS is that the latter incorporates a gravity measuring instrument, viz a gravimeter. The requisite space and power for the gravimeter have already been designed into the GSS ADM platform so that only the gravimeter and its associated electronics need be added. The existing space already designed into the Gravity Sensors Platform is sufficient to house at least two gravimeter sensors. The associated gravity data buffer electronics will be housed in the electronic cabinets, and the data processing will be performed by the Dedicated Operational Computer.

#### 6.7 The Gravity Gradient Instrument

The analyses presented in Section 4.0 indicate that further improvement or reduction in the noise level of the Bell ADM GGI is not warranted for gravity mapping missions of rectangular areas less than 200 km per side. The reduction obtainable in the gravity mapping errors resulting from an improvement in the GGI self generated noise level is not, in these cases, sufficient to warrant a major redesign of the GGI. However, it is planned to reduce the instrument noise to  $10E^2/\text{rad/sec}$  to remove possible limitations on mission duration. These levels have been achieved in some instruments and BAT is engaged in an ongoing program to identify error sources and consistently produce instruments with a noise level

less than  $10E^2$ /rad/sec. Work to date indicates that this is achievable by simple design changes. Error sources being actively investigated include:

- Bell Model VII-G Accelerometer Sensor
- Bell Model VII-G Accelerometer Electronics
- Detection Electronics
- Electronic Noise in the Compensation Loops and the Fixed Level Compensations
- Electronic Noise in the Off-Rotor Electronics
- Noise from the Dynamics of Rotation
- System Integration Effects
- Instrument Sensitivities to
  - Ambient Temperature
  - Humidity
  - Magnetic Fields
  - Pressure
  - Linear and Angular Vibrations

These error sources are addressed in more detail in Section 7.0.



## 7.0 TECHNICAL DESCRIPTION/TRADEOFFS OF THE IGMS CONFIGURATION

### 7.1 General

This section describes the IGMS based on the considerations of the foregoing sections. The material of earlier sections is restated where appropriate to consolidate the description. In defining the IGMS, this section will discuss the resolution of the tradeoff considerations which were raised in Section 6.0. The selection of the INS and computers were narrowed to a pair of candidates for each and the remaining tradeoffs between them discussed. The final selection of the INS and computers will be made after further evaluation. This does not alter the system description significantly.

The Integrated Gravity Mapping System (IGMS) will be a self contained, "turn-key" package. All subsystems will be mounted to standard pallets, readily transportable and adaptable for installation on the selected vehicles. Only external primary power will be required for IGMS operation. Operator participation is minimal. The subsystems will be modified versions of the ADM GSS plus a standard Inertial Navigation System.

The major units and the sections in which they are discussed are:

- 7.2 Gravity Gradiometer Instrument (GGI)
- 7.3 Inertial Navigation System (INS)
- 7.4 Binnacle, Cooling System and Shock/Vibration Isolators
- 7.5 Gravity Sensor Platform (GSP)
- 7.6 Dedicated Operational Computer (DOC)
- 7.7 IGMS Operational Computer Program
- 7.8 Gravity Gradiometer Electronic Cabinets (GGEC's)

The ADM GSS subsystems which will be adapted for the IGMS are described in Section 3.0 and shown in the composite photograph of Figure 7-1.

### 7.2 Gravity Gradiometer Instrument

As described in Section 3.7 and Appendix A, the key design features of the Bell rotating accelerometer gradiometer are the use of rotation to modulate the gravity gradients at twice per wheel revolution in order to modulate the gravity gradients at twice per revolution, and to allow the use of automatic closed loop compensation techniques to provide the moving base capability. The performance

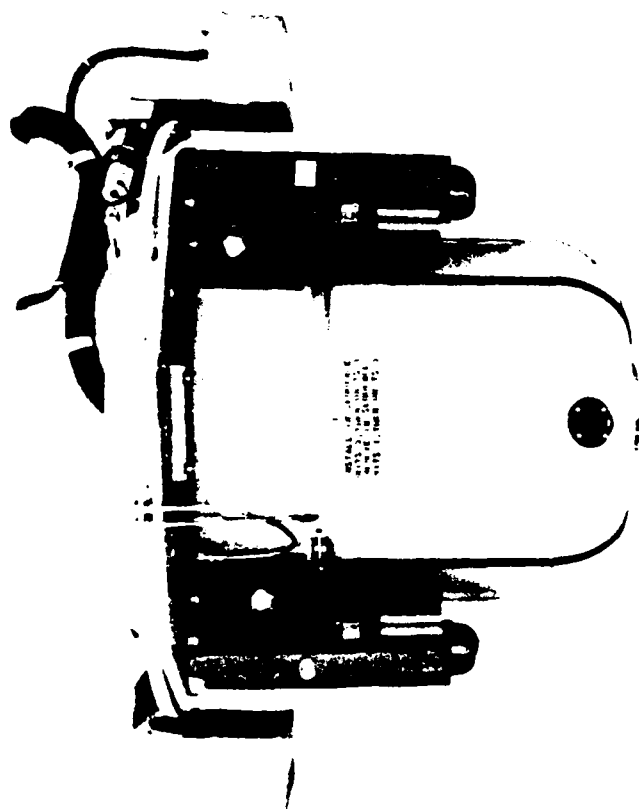
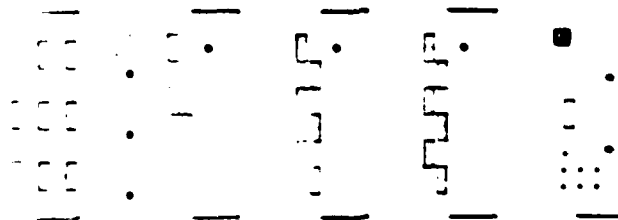
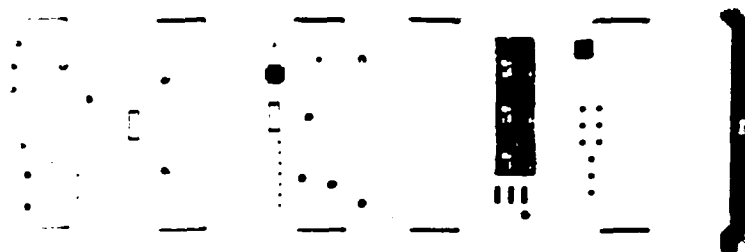


FIGURE 7-1. COMPOSITE PHOTOGRAPH OF THE GSS ADM EQUIPMENT



of a gradiometer or gradiometer system is usually expressed by an output error spectrum which is the power spectral density of the output error from all sources. This includes the environment acting on environmental sensitivities and the instrument self generated noise.

For the GSS ADM application, the frequency domain of prime interest is around  $10^{-5}$  rad/sec and to a lesser extent at the Schuler frequency. For the IGMS mapping application, the higher vehicle speeds shift the region of concern to the higher frequencies between  $10^{-3}$  and  $10^{-1}$  rad/sec. Based on the analyses presented in Section 4.0, expected to be verified by the ongoing exact analysis, a white noise level in this frequency region of  $10E^2$ /rad/sec is sufficient for IGMS missions of any practical length.

BAT is maintaining an active, ongoing program to improve GGI performance by identification and correction of error mechanisms. Under the sponsorship of SAMSO, the goal set was for a white noise level of  $10E^2$ /rad/sec, and the Bell rotating accelerometer gradiometer was consequently designed toward that goal. However, in the development work conducted under the more recent sponsorship of the US Navy, there has been no emphasis on improving nor indeed on consistently achieving reduction in the inherent high frequency white noise level. This was not an important requirement for the Navy program.

In addition to the high frequency noise from self generated mechanisms, the environmental sensitivities of potential concern to the IGMS application are:

- Linear Vibration Sensitivity
- Pressure Sensitivity (Aircraft Application Only)
- Angular Vibration Sensitivity

Other environmental sensitivities to magnetic fields, temperature, humidity have been demonstrated by test to be negligibly small.

#### 7.2.1 Self Generated Noise Performance

The self generated noise performance for the present ADM GGI design is shown in Figure 3-41 of the Volume IV classified addendum. The flat or white noise level of the spectrum is very close to the original SAMSO objective of  $10E^2$ /rad/sec for S/N 107, but a more typical magnitude is  $25E^2$ /rad/sec.

Test of GGI subsystems indicate that without significant changes it should be possible to consistently achieve performance significantly better than  $25E^2/\text{rad/sec}$ .

The contribution from the subsystems is shown in Table 7-1.

Source	White Noise Power $E^2/\text{rad/sec}$
Model VII-G Accelerometer Sensor	$\triangle$
Model VII-G Constraint Electronics	$\triangle$
Detection Electronics	$\triangle$
Electronic Noise in Compensation Loops and Fixed Level Compensation	$\triangle$
Total	$\triangle$

TABLE 7-1. IGMS GGI PROJECTED ERROR ALLOCATIONS

$\triangle$  Data is classified CONFIDENTIAL. See Volume IV classified addendum to this report for this page complete with classified data.

Potential sources of noise that should be added to this listing for the IGMS application are:

- Electronic noise in off rotor electronics (in a test set or operating cabinet)
- Noise from the dynamics of rotation
- Noise from a mechanism resulting from the combination of the individual subassemblies in an integrated instrument system

For the IGMS mapping application, all noise sources will be reviewed and minimized by appropriate design changes. For example, the detection electronics contribution of  $4E^2/\text{rad/sec}$  can simply be reduced by using fewer torque coil turns in the accelerometer, and consequently raising the restoring  $\text{ma/g}$ . The power noise in the detection electronics will vary by the square of the change ratio so that a doubling of the  $\text{ma/g}$  will result in the noise declining to  $1E^2/\text{rad/sec}$ .

A second area in which a simple change can potentially result in reduced noise, relates to rotor speed. The  $5E^2/\text{rad/sec}$  directly attributable to the accelerometers sensor stems from a noise term of the form:  $10 \text{ noise} = Bf^x$  where

B = constant

f = frequency at which the noise is measured

x = exponent

The value of x is in the order of -0.6. Thus, the magnitude of this term decreases with increasing frequency, i.e., increasing rotor speed. Although not directly addressed for some time primarily because the Navy requirement was satisfied by the current instruments, earlier GGI tests indicated that at low speeds ( $\frac{1}{4}$  Hz and below) the added noise from rotation was small with respect to  $10E^2/\text{rad/sec}$ , but that at higher speeds ( $\frac{1}{4}$  Hz and above), the noise increased from the dynamics of rotation. The possibility of an optimum speed somewhat greater than  $\frac{1}{4}$  Hz that minimizes the white noise level is currently under active investigation.

#### 7.2.2 Environmental Sensitivities (U)

Table 7-2 lists the GGI projected environmental sensitivities for the IGMS mapping system. As stated in earlier sections, the linear vibration sensitivities at critical frequencies and the sensitivity to magnetic fields are the principal concern

Environment	Sensitivity
Ambient Temperature	$\triangle$
Humidity	$\triangle$
Magnetic Fields	$\triangle$
Pressure	$\triangle$
Linear Vibration at Critical Frequencies $1\Omega$ , $2\Omega$ , $3\Omega$	$\triangle$

TABLE 7-2. IGMS GGI PROJECTED ENVIRONMENTAL SENSITIVITIES

$\triangle$  Data is classified CONFIDENTIAL. See Volume IV classified addendum to this report for this page complete with classified data.

The angular sensitivity has already been shown by the NS Vanguard shipboard tests to be no problem because of the high gain stabilization loops of the platform. Aboard this test ship, roll angles in excess of  $30^{\circ}$  p-p have been experienced without degradation of GGI performance.

The sensitivity to ambient pressure is believed due to the accelerometer case design. This is being actively investigated and the levels of Table 7-2 are believed within reach.

Tests aboard the NS Vanguard and at Bell are being conducted to identify and reduce the error mechanisms for sensitivity at the critical frequencies. Reduction to the levels of Table 7-2 are achievable. With the projected sensitivities, all the requirements of the IGMS will be met.

### 7.3 Inertial Navigation System (INS)

The Inertial Navigation System (INS) is required to provide continuous position and velocity information and pallet attitude angles. The position information identifies the survey points at which the gravity anomalies and deflection of the vertical are mapped. Velocity and pallet attitude angles are used to level and align the Gravity Sensor Platform (GSP).

The GSP has its own leveling accelerometers. However, as currently configured, the platform is not self-aligning. The azimuth synchro information from the INS is used to North align the GSP; i.e., the GSP azimuth is synchro slaved to the INS. The GSP platform is controlled by operating it as a navigator with the NAV equations being solved in the Dedicated Operational Computer (DOC). Velocity updates from the INS trim platform tilt errors and fine trim the alignment.

Since typical candidate test aircraft already carry an inertial navigator, the question of whether to use the vehicle's INS or a separate INS dedicated to the IGMS is pertinent. For the land vehicle surveying applications, an INS must be incorporated in the IGMS configuration since these vehicles are assumed to not be equipped with INS systems.

For fixed wing aircraft, the following disadvantages arise from the use of the aircraft's own INS.

- a) Interfacing problems arise which are unique to each vehicle used.

As an example of this, the GSS ADM as operated on board ship required specific software modifications before successful interfacing with the ship's SINS was achieved.

- b) The accuracy of gravity mapping would vary depending on the performance of the INS found on the aircraft. This INS would not be specifically tailored to the gravity mapping mission.
- c) Errors would result due to the relative movement between the INS and the IGMS platform/binnacle. Relative motion exists because both are individually shock and vibration isolated and at different locations on the vehicle.

The principal advantage of using the aircraft's own INS is, of course, that the equipment is already installed and tested in the vehicle and would consequently reflect a cost saving. This saving, however, would obviously not survive if a shift to a land vehicle became necessary or desirable.

Based on these observations and noting that the land based vehicle would in all probability not carry its own INS and also noting the desirability of a common system for all applications, it has been decided that a dedicated INS will be used for all IGMS applications.

A tradeoff following from this decision is whether the dedicated INS should be a separate piece of equipment or mounted integrally with the platform/binnacle.

The main disadvantage of using a common mounting base (or bedplate) for both the INS and the platform/binnacle is that the mounting base (or bedplate) and the shock/vibration isolation system as presently used on the GSS ADM system would have to be redesigned. This is not a major consideration since the redesign is a straightforward application of state-of-the-art technology. This is discussed further in Section 6.0. This disadvantage is outweighed by the following advantages which support the choice of a common bedplate.

- 1) The resulting IGMS would be a "turn-key" system, i.e., the system would be designed and built as a self contained system which is not dependent on any support from other "outside" systems other than primary power. The complete IGMS (including the INS) would be designed and fabricated as a single assembly.
- 2) This design would eliminate the errors resulting from the relative motion that would otherwise occur between the INS and IGMS platform/binnacle.
- 3) Interfacing problems between the INS and IGMS would be defined and solved before fabrication and test of the system.

Four INS vendors were contacted for data to evaluate the suitability of their systems for the IGMS. The results are summarized in Figures 7-2 through 7-5.

The selection criteria are:

- (a) Meeting performance requirements
- (b) Reliability
- (c) Cost
- (d) Commonality for all vehicles

Detailed analysis of INS requirements are being performed and will be completed before the anticipated go-ahead date for the mapping system. However, preliminary analyses, which will be substantiated by the detailed study, show that a 1 nmph system is adequate for land vehicles and helicopters where ZUPTS enable updates giving a high effective accuracy. The increasing emphasis on mapping via fixed wing aircraft suggests a requirement for a higher accuracy navigator because of the absence of ZUPT update capability. The simplified analysis of Section 4.0, however, shows that, if the airborne mission is optimally selected to make the maximum use of "tie-points", this higher accuracy requirement may be relaxed substantially. This will be verified by the detailed analysis.

The results of this preliminary tradeoff analyses thus indicate that:

- The AN/ASN-136 has the best accuracy-to-cost ratio and is the first choice if the high accuracy is needed. Figure 7-6 shows the AN/ASN-136.
- The Litton LN-39 would become the first choice if a 1 nmph system is shown to be adequate for the airborne applications. Figure 7-7 shows the LN-39.
- The desirability of commonality, leads to the tentative selection of the same INS for all vehicle applications.
- Reliability data for the AN/ASN-136 need to be further evaluated particularly for the land vehicle and helicopter environments before the commonality decision is finalized.

All cost figures in Figure 7-2 are ROM figures based on telephone contacts. Experience, however, indicates that firm figures are generally higher than the initial ROM estimate elicited.



- DELCO
  - Detailed Data Received
  - 0.7 nmph System
  - Commercial System
  - Arinc and MIL-STD Interfaces Available
  - \$110,000 ROM\*
- HONEYWELL
  - Detailed Data Received
  - 0.1 nmph System
  - Commercial and Military
  - Gravity and Magnetic Mapping Contracts
  - MIL-STD Interface
  - \$176K (AN/ASN-136 (No Computer) ROM\*
  - \$635K Full Up Surveying System ROM\*
- LITTON
  - Detailed Data Received
  - 0.8 nmph System Standard
  - Military
  - \$100K ROM
  - MIL-STD Interface
  - Pads - Gravity Mapping
  - 0.25 nmph System
  - MIL-STD Interface
  - \$200K ROM\*
- KEARFOTT
  - Telephoned Data Only
  - 0.6 nmph Standard System \$100K ROM\*
  - 0.25 nmph in Development \$300K ROM\*

\*Listed costs are based on preliminary communications. Firm quotes may show significant variations.

FIGURE 7-2. VENDORS CONTACTED (SUMMARY)

DELCO

- Essentially Commercial - Do Supply MIL-STD I/O for C4A

- Specs

Position	0.7 nmph
Velocity	Limited Data - Said to be Minimized by Carouseling
Size	$\approx 2 \text{ ft}^3$
Weight	92 lbs, BU 27 lbs
Power	365W

FIGURE 7-3. DELCO CAROUSEL

LITTON

- Standard Navigator

Interface MIL-STD-1553

- Specs

Position	0.8 nmph
Velocity	2.5 fps
Weight	41 lbs
Size	$0.5 \text{ ft}^3$
Power	180W

- Pads - Survey System

High Accuracy with ZUPTS

FIGURE 7-4. LITTON LN-39

HONEYWELL

- Standard Precision Navigator

GEANS, A SN101, SPN GEANS, ASN131  
1969 thru present  
Lance, 727, RC135, B52, C141, Survey Work

- Specs

	<u>SPN/GEANS</u>	<u>AN/ASN-36</u>
Position	0.1 nmph	0.12 nmph
Velocity	2 fps/axis	2 fps/axis
Hdng	3.0 arc min	3.0 arc min
Attit	3.0 arc min	3.0 arc min
React Time	25 min	90 min air align
Cal Interv	150 days	365 days
IMU/IEU		
Size	1.9 ft <sup>3</sup>	1.9 ft <sup>3</sup>
Wght	120 lbs	120 lbs
Power	700W	410W
Interface	MIL-STD-1553	MIL-STD-1533

- Geo-Spin

ETL, DMA Surveys (Land Van, Heli, Fxd Wing Air) Gravity and Mag Field Surveys

FIGURE 7-5. HONEYWELL

# AN/ASN-136

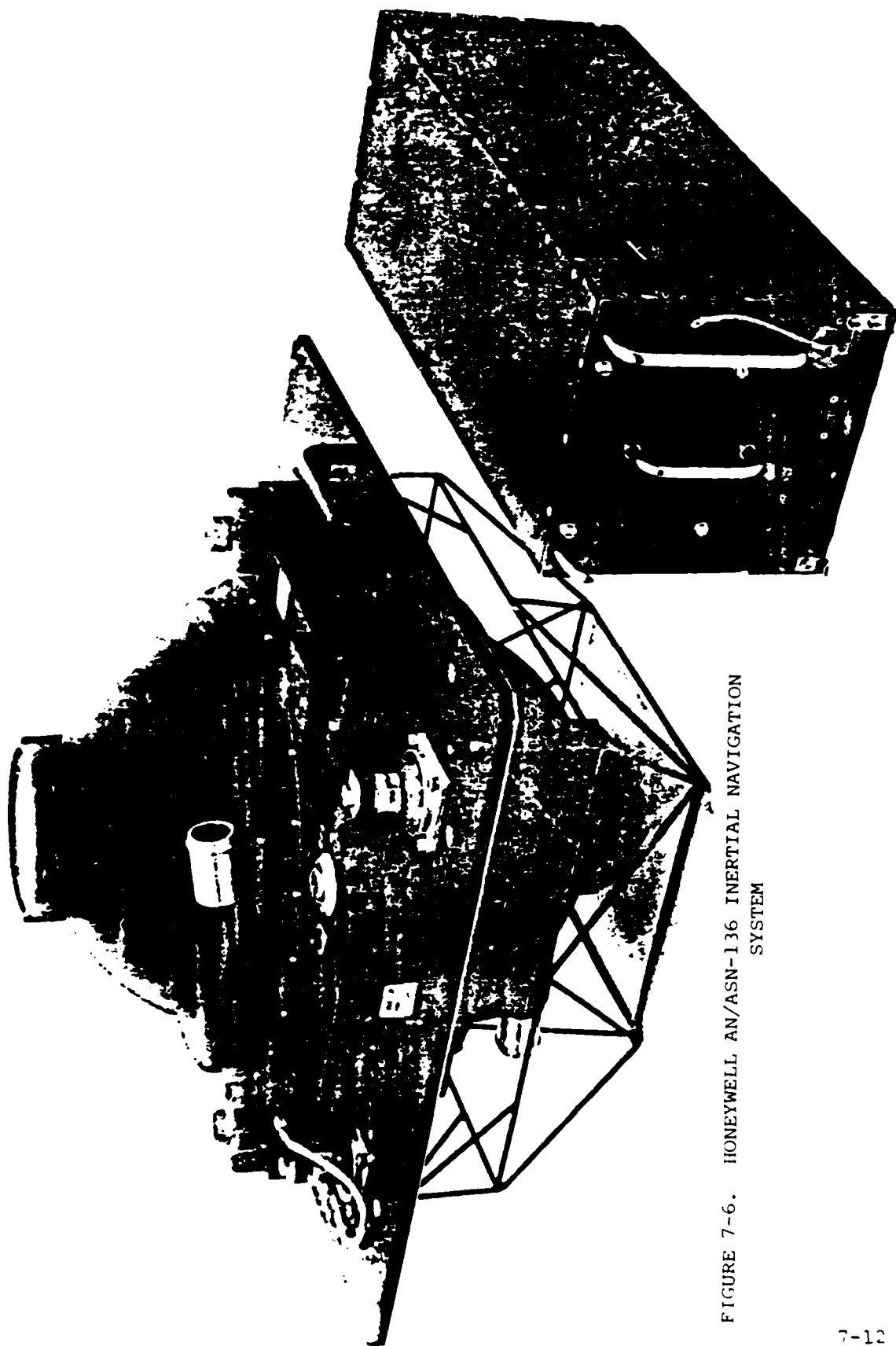
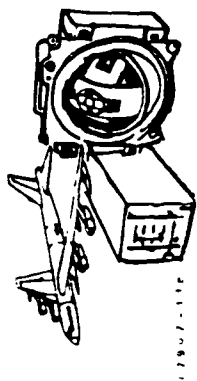


FIGURE 7-6. HONEYWELL AN/ASN-136 INERTIAL NAVIGATION SYSTEM

# LN-39 INU EXPLODED VIEW

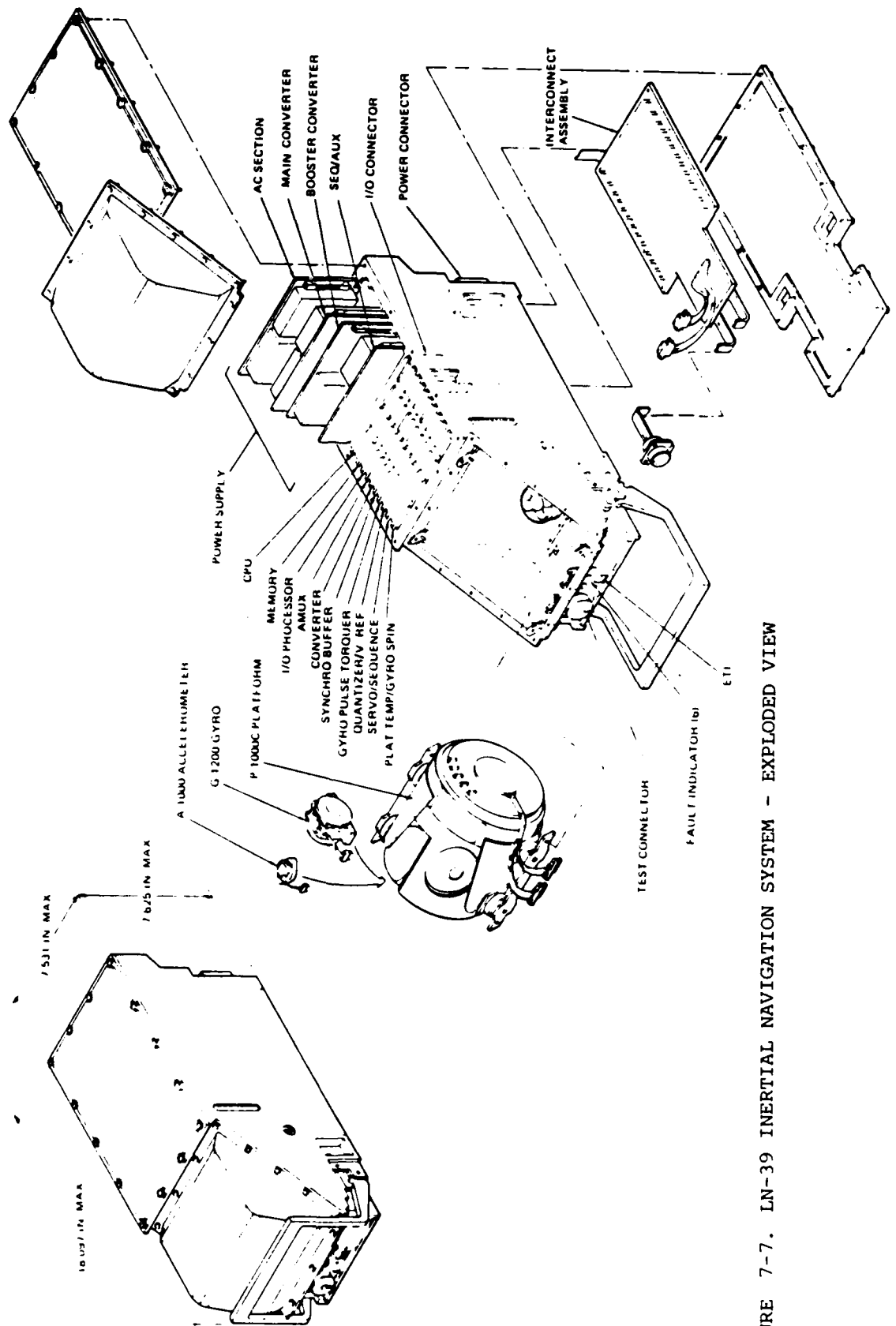


FIGURE 7-7. LN-39 INERTIAL NAVIGATION SYSTEM - EXPLODED VIEW

#### 7.4 Platform Enclosure (Binnacle), Cooling System and Shock/Vibration Isolators

The Binnacle and the closely associated cooling system along with the isolator comprise all of the equipment necessary to mount the platform to the vehicle while providing isolation from thermal and vibratory stimuli induced by the vehicle environment. These systems will exhibit the most visible changes between the current GSS ADM and the IGMS. The ultimate design for the IGMS will use as much of the current GSS ADM design as possible but significant modifications are indicated by the following considerations:

1. Changing from an overhead mounting to a floor mounting of the Binnacle Equipment to the vehicle. The existing GSS ADM platform/binnacle is top mounted to an overhead bedplate on the test ship. This design was dictated by the allocated space aboard ship for the system. For the IGMS, this space constraint is not valid.
2. The incorporation of the navigator as part of the Binnacle Equipment, to be mounted on a common rigid structure with the Gravity Sensor Platform (GSP) as discussed in 7.3 above.

Tradeoffs between two approaches were studied:

1. Design a new Binnacle from the ground-up, incorporating the specific features as required for the gravity mapping mission and eliminating inapplicable restrictions imposed by the Navy equipment guideline specifications on the existing Binnacle design.
2. Utilize as much of the existing Binnacle design as possible, making modifications as required to satisfy the mapping application.

Approach (2) on initial consideration appears attractive because it suggests reduction in non-recurring costs and minimization of risk in certain detail areas. In depth studies, however, favor design approach (1). Advantages of a newly designed Binnacle over modifying the existing equipment design are:

1. The design will be functionally superior, addressing from the onset the requirement for (a) a rigid structural coupling and alignment between the gradiometer platform and a navigator platform and (b) floor mounting of the Binnacle Equipment.

2. The design will not be subject to requirements necessary for the intended naval application but which are not applicable to the gravity mapping mission. The new design will be less complex, less expensive (recurring costs) and both lighter and smaller than the current design would be after modifications for the IGMS are incorporated.

The necessary requirements on the GSS-ADM design which are not applicable for IGMS include:

- Overhead mount
  - Precision returnability vibration isolator
  - Precision multiple optics and optical windows
  - Transport through a 25 inch diameter hatch
  - Water cooling with on-board heat exchanger and blower fan
  - Shape-factor limits specific to submarine bedplate mounting requirements
3. The proposed new design air cooling will be simpler and more efficient than the present water cooled equipment. Concerns that additional technical risks may be associated with "new design" vs "tested system" are not valid since the "tested system" will also require design changes. The "tested system", if used for the mapping mission, would be inverted (with respect to the "g-vector") from its tested orientation. This reverses all the patterns of convective "chimney effects" of the air flow within the Binnacle, to the detriment of overall cooling performance.
  4. The new design totally encloses the vibration isolators and the isolated structure. This increases the isolation of the INS and GSP platforms from inadvertent mechanical disturbances such as attending personnel contacting the structure when working around the equipment. The current Binnacle design after modification for the IGMS would have the isolated structure exposed.
  5. The new design is expected to be overall more cost effective, both in quantity production and on a 1 or 2 system basis. The non-recurring costs required for design of the new Binnacle are offset by two factors:
    - (a) Design mods to the existing Binnacle will incur significant non-recurring costs.
    - (b) Fabrication and assembly of the new design Binnacle will be less costly than for the current design, modified or unmodified.

6. Reduced complexity of Binnacle arrangement and detail parts configuration will reduce purchased parts lead times, thus being more supportive of a tight program schedule.

The design studies for the Binnacle/cooling system are continuing. A description of the configuration which has evolved to date follows. Figures 7-8 and 7-9 are layouts of the proposed design. The Binnacle will be a rectangular box with dimensions as shown in these figures, with a weight, including platform, roughly estimated at 750 lbs. The outer enclosure will provide thermal insulation and mechanical protection, and will be fitted with a removable cover for internal access. Bulkhead connectors will be included in a fixed lower side wall of the enclosure to provide electrical and cooling air interface to the system. Within the Binnacle, four vibration isolator elements will be located symmetrically about the C.G. of the Gradiometer Platform/Navigator Assembly. From experience gained from the GSS ADM equipment, an 8-10 Hz isolator system will be required for the IGMS application. The existing GSS ADM vibration isolator uses low damping C springs for good returnability to the null position. Returnability is not a problem in the IGMS system since the platform/binnacle is mounted on a common bedplate with the INS. Because of the relaxation of the returnability constraint, the C springs are not required and conventional rubber isolators with low damping would be sufficient. The selected vibration isolators would be existing manufacturer's vibration isolators selected to attenuate frequencies above 10 Hz with a Q of 3 to 4.

#### 7.5 Gravity Sensors Platform

The existing three axis stabilized platform configuration as designed, built and tested by Bell for the US Navy (SP-24) under the currently funded Advanced Development Model program, will be used virtually unchanged for the gravity mapping system. This platform is described in detail in Section 3.0 and again illustrated in the cutaway drawing of Figure 7-10. The only significant difference for the IGMS application will be the method of mounting the outer frame of the platform to an isolated structure within the protective Binnacle enclosure. The Gradiometer Platform/Navigator Assembly will be built up by bolting on some additional structure to the existing design platform outer frame. This structure will serve to mount the navigator so as to be rigidly coupled and aligned (mechanically) to the Gradiometer Platform. This structure will also provide the mechanical interface to connect to, and be supported by, the four vibration isolator elements. Binnacle



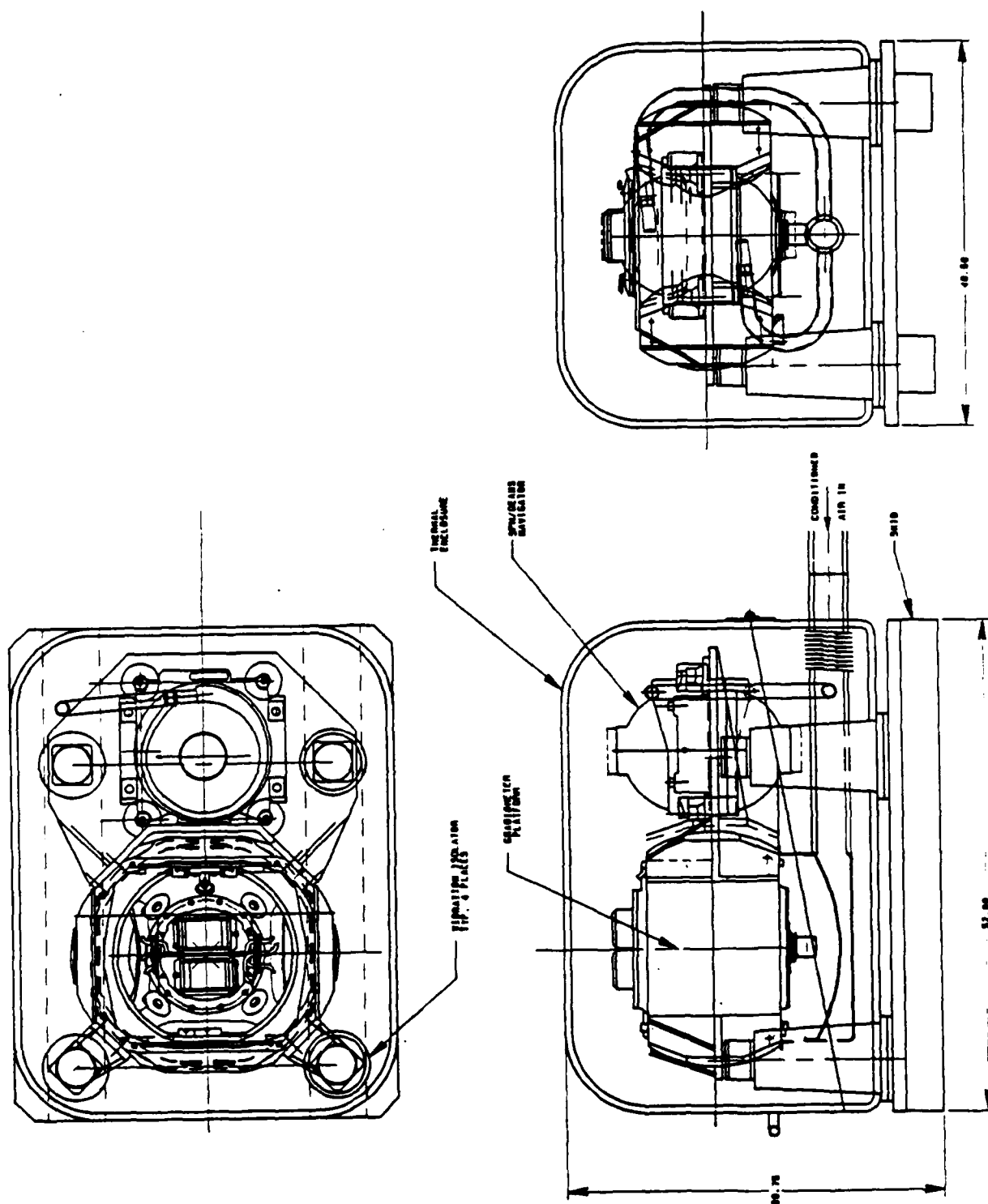


FIGURE 7-8. PLATFORM/ENCLOSURE ARRANGEMENT WITH SPN/GEANS NAVIGATOR

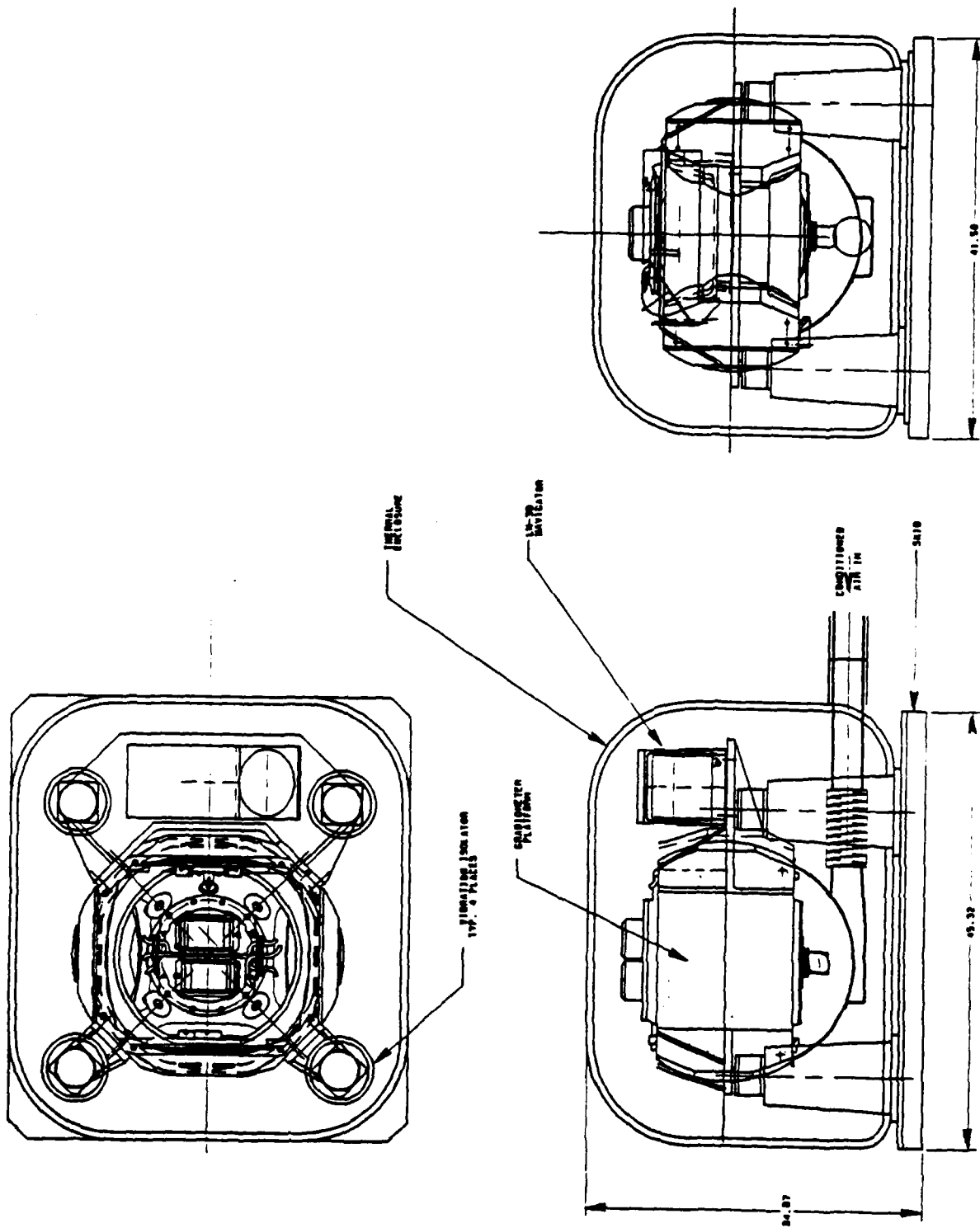


FIGURE 7-9. PLATO 11 ENCLOSURE ARRANGEMENT WITH LN-39 NAVIGATOR

temperature will be controlled by a supply of chilled, temperature controlled air, ducted through the Binnacle enclosure and into the bottom of Gradiometer Platform. The air will exit from the top of the Platform, circulate within the Binnacle interior, and escape from lowered openings near the bottom of the enclosure. The chilled air will be supplied by a small (<12,000 Btu/hr) air conditioning unit. This unit need not be mounted to the same pallet as the Binnacle. For transportability, it is planned that this be a separate system with hose connector to the Binnacle.

Table 7-3 shows the heat load for the various configurations which were used to assess cooling system requirements.

#### 7.6 Dedicated Operational Computer (DOC)

The GSS ADM under development for the Strategic System Project Office of the US Navy utilizes the Government furnished Digital Equipment Corporation's VAX-11/780 digital computer modified for the anticipated Naval Test Vehicle environment. The potentially more severe environment of the IGMS inherent in the wide variation of mapping vehicles and mission profiles requires the selection of a more rugged computer.

A preliminary survey of available and suitable ruggedized computers meeting the memory and speed requirements indicates that the suitable candidates are limited. These are listed in Table 7-4, together with a summary of their characteristics. The candidates selected on a price/performance basis for the IGMS application are the ROLM MSE-14, and the NORDEN PDP-11/70M, with the software written in Fortran.

The tradeoff considerations narrowing the selection to these two are as follows. As outlined in Sections 6.0, the development and operation of the IGMS system will require four distinct computer operations. These operations are:

- Software generation system
- Land vehicle based operational computer
- Airborne operational computer
- Post mission data reduction system

Analysis indicates that these four separate requirements are optimally satisfied by procurement of three computers. The two operational computers will be the same type.

TABLE 7-3. ESTIMATED HEAT LOADS FOR COOLING SYSTEMS

1) SPN-GEANS Located Inside Common Thermal Enclosure - Open Air Loop Air Cooled System

Ambient °F	Air-Conditioner	SPN-GEANS		Binnacle Heat Load	External		Total Heat Added
		Air load	Binnacle Load		SPN-GEANS Load		
46°F	3070W	500W	80W	-150W	220W	3720W	
66°F	-	-	80W	-	220W	300W	
86°F	-3070W	-500W	80W	150W	220W	-3120W	

2) Litton LN-39 Located Inside Common Thermal Enclosure - Open Air Loop Air Cooled System

Ambient	Air-Conditioner	LN-39		Binnacle Heat Load	External		Total Heat Added
		Air Load	Binnacle Load		Binnacle Load	Litton LN-39 Load	
46 °F	3070W	440W	80W	-122W	180W	3648W	
66 °F	-	-	80W	-	180W	260W	
86 °F	-3070W	-440W	80W	122W	180W	-3138W	

3) SPN-GEANS Located Outside IGMS Thermal Enclosure - Closed Air Loop/Water Cooled System

Ambient °F	Air-Conditioner for SPN-GEANS		SPN-GEANS		External		GSP Heat	SPN Heat Added
	Air Load	Binnacle Heat Load	Binnacle Load	SPN-GEANS Load				
46 °F	-	500W	354W	- 70W	220W	284W	720W	
66 °F	-	-	257W	-	220W	257W	220W	
86 °F	-	-500W	160W	70W	220W	230W	-280W	

4) Litton LN-39 Located Outside IGMS Thermal Enclosure

Ambient	Litton LN-39		External		Litton LN-39	
	Air Load	Binnacle Heat Load	Binnacle Load	Load	GSP Heat	LN-39 Heat Added
46 °F	440W	354W	-70W	180W	284W	620W
66 °F	-	257W	-	180W	257W	180W
86 °F	-440W	160W	70W	180W	230W	-260W

TABLE 7-4

## MILITARIZED MINICOMPUTERS SUITABLE FOR DMA

COMPUTER MANUFACTURER	NORDEN	NORDEN	HONEYWELL	IBM	IBM	IBM	SPERRY DEFENSE SYS	CONTROL DATA CORPORATION	ROMA	ROMA
Model No.	PDP-11/44M (AN/UYK-42(U))	PDP-11/70M (AN/UYK-42(U))	RL-6 (Level 6)	CC2	API01C	MIL-STD-1750	MIL-STD-1750	AN/AYK-14(U)	MSS-14 (AN/UYK-19(U))	1666B (AN/UYK-19(U))
Max. Memory (Bytes)	512K	L096K	1024K	1024K	1024K	1024K	2048K	2048K	512K	512K
CPU Speed	500K OPS	850K OPS		2000K OPS	500K OPS	500K OPS	700K OPS	900K OPS	830K OPS	500K OPS
I/O Speed	1.1 MM/sec	5.8 MM/sec				5.8 MB/sec		500K W/sec		
Floating Point Hardware	Yes 16.2 µsec	Yes	Yes	Yes	Yes	Yes	Yes	Yes 8 µsec	Yes	Yes
Language	Fortran Basic	Fortran Basic	Fortran	370 Compatible	Jovial	Jovial	CMS-2 Jovial	CMS-2 Fortran	Fortran	Fortran
Remarks	Based on DEC PDP-11/44	Based on DEC PDP-11/70 32 bit word length		Based on IBM 360/370	32 bit word length	32 bit word length		Navy Standard Airborne Computer	Based on Data General Eclipse	Based on DEC Nova
Size/ Weight	1-ATR 65 lbs	4-ATR 260 lbs	13"x17.5"x26.6" 130 lbs	75"x45"x20" 900 lbs	1-ATR 45 lb	1-ATR 50 lbs	1-ATR	1-ATR 90 lbs		

The Operational computers must be ruggedized and mated with ruggedized peripherals. Commonality considerations dictate that the same ruggedized computer type be selected for the Airborne and Land vehicle applications. The software generation and data reduction function will be satisfied by one computer, which is software compatible with the operational computers.

Consider first the operational computers. To make a selection of the operational computer type from those available on the market, the following factors were considered:

- a) Language - The GSS ADM computer program is written in Pascal. Simplicity of adaptation makes this the most cost effective language, but the tradeoff analyses show that this is not available. Consequently, Fortran was selected as the next desired language. Fortran is used extensively at Bell and is considered as a very acceptable alternative.
- b) Memory Requirements - The operational portion of the GSS ADM computer program requires approximately 512K bytes of memory. The IGMS DOC requirements will be similar.
- c) Timing Requirements - The GSS ADM computer - a DEC VAX-11/780 computer is a fast computer with a CPU speed exceeding 1,000 kiloperations per second (KOPS). The IGMS computation will require similar speed. A lower limit not less than 700 KOPS is specified.
- d) Size - Since the IGMS computer will be installed aboard a truck and an airplane, small physical size is specified.
- e) Power and Cooling Requirements - The IGMS computer power and cooling requirements must be compatible with the power and ambient environment imposed by the selected vehicles.
- f) Environment - Because of the shock and vibration levels anticipated on the selected test vehicles, the IGMS operational computer will have to be ruggedized to insure normal operation at these vibration levels.

The survey of available and suitable ruggedized computers, particularly with respect to the BYTE and KOPS capacity cited in b) and c) above, narrows the choices to the ROLM MSE-14, and the NORDEN PDP-11/70M.

Consider now the computer selection for the software generation system and the post mission data reduction system. The software generation system is required to

yield Operational Computer compatible software. Similarly, the post mission data reduction system must read magnetic tape data produced by the Operational Computers. This compatibility with the Operational Computer drives the selection. The software generation system can be a second operational computer (i.e., fully ruggedized but with additional peripherals which need not be ruggedized) or a commercial computer which is fully software compatible with the selected Operational Computer. The tradeoff results indicate that the latter approach is the most cost effective.

Bell has had extensive experience with DEC PDP-11, Data General Eclipse and IBM-370 computers. These are commercial off-the-shelf computers and are fully software compatible with the candidate Operational Computers. Bell will select one of these for the software generation/post mission data reduction function, based primarily on the costs: initial and maintenance support.

#### 7.7 The IGMS Operational Computer Program

The software which will reside in the operational computer will enable the computer to perform the same basic functions provided by the ADM GSS software as described in Section 3.0 and Appendix B. These functions provide for the following.

- Gravity Gradient Tensor Solution in NED Coordinate System
- Inertial Instrument Calibration, Computation and Compensation
- Alignment to the Leveling to INS Coordinates
- Data Analysis Statistics
- Data Recording

In order to provide these functions, the twenty software functions which were originally designed and programmed for the GSS ADM System (described in Section 3.0 and Appendix B) will be used, either modified or directly, for this application. These original functions were characterized in the following groups.

##### A. Calibration Functions

- Accelerometer Calibration
- Gyro Calibration
- GGI Scale Factor Calibration
- Prepermission Calibration

B. GGI Processing Functions

- Gimbal Self Gradient (Compensation)
- GGI Compensation (Including Vehicle Self Gradients)
- Gradient to Tensor Processing
- Tensor Rotation and Decarouseling
- Performance Monitor

C. Platform Control Functions

- Diagnostics
- Status and Control
- Accelerometer Compensation and Resolution
- Attitude Command
- Platform Control
- Resolution and Gyro Compensation

D. System Control Functions

- Start Up and Operator Control
- Program Control (Control Process)
- Input/Output Control
- Peripheral I/O (includes magnetic tape data logging)
- System Affiliated

Of these twenty developed GSS ADM functions, the following functions will be modified for the IGMS application because of subsystem changes and additions - viz the INS and the computer and the inclusion of a gravimeter:

- Platform Control
- Operator Control
- Input/Output Control
- Peripheral I/O
- Program Control
- System Affiliated
- Performance Monitor

In addition, further functions viz:

- Platform Calibration
- Gimbal/Vehicle Self Gradient Identification

will be included to facilitate system installation and calibration aboard the vehicle.



Since the objective of this application is that the primary data be obtained by using post mission processing, the functions included in Group B as mentioned above will be included to achieve a "quick look" capability only if the time burden of the IGMS operational computer permits. If a time problem is uncovered following a preliminary timing analysis based on the selected computer, some or all of these functions will be omitted from the operational computer program.

Appendix B contains brief descriptions of the theory of operation of the more significant functions.

To support the inclusion of the gravimeter, additional software will be included to perform the following tasks:

- Store critical constants such as gravity sensor scale factor and bias required for use in computations.
- Perform all the calculations required to filter, scale and bias the gravity data and reduce the data to free air anomalies.
- Format and log the data for recording on the magnetic tape.
- Format and record data to provide a continuous 24 hour minimum history for review if requested.
- Provide, on command, a printout of the critical constants currently being used by the calculator.
- Provide an easy method of modifying the constants when required.

The software is basically the same as has been in use on Bell Gravity Meter Systems for many years and has been thoroughly developed and tested.

#### 7.8 Gravity Gradiometer Electronic Cabinets (GGEC's)

The two GGEC's are electronic cabinets which house all the IGMS electronic circuits and components which are not mounted on GGI's or the platform, excluding: of course, the DOC and INS which are independent, stand-alone systems. The two cabinets referred to as GGEC #1 and GGEC #2 are differentiated by their basic functions. GGEC #1 controls the GGI's and GGEC #2 controls the platform and formats and exchanges data with the DOC.

Figure 7-10 shows the layout of these cabinets with the subsystem drawers identified. These cabinets with the exception of the slight modifications described below are identical to the two GSS electronic cabinets described in detail in Section 3.0.

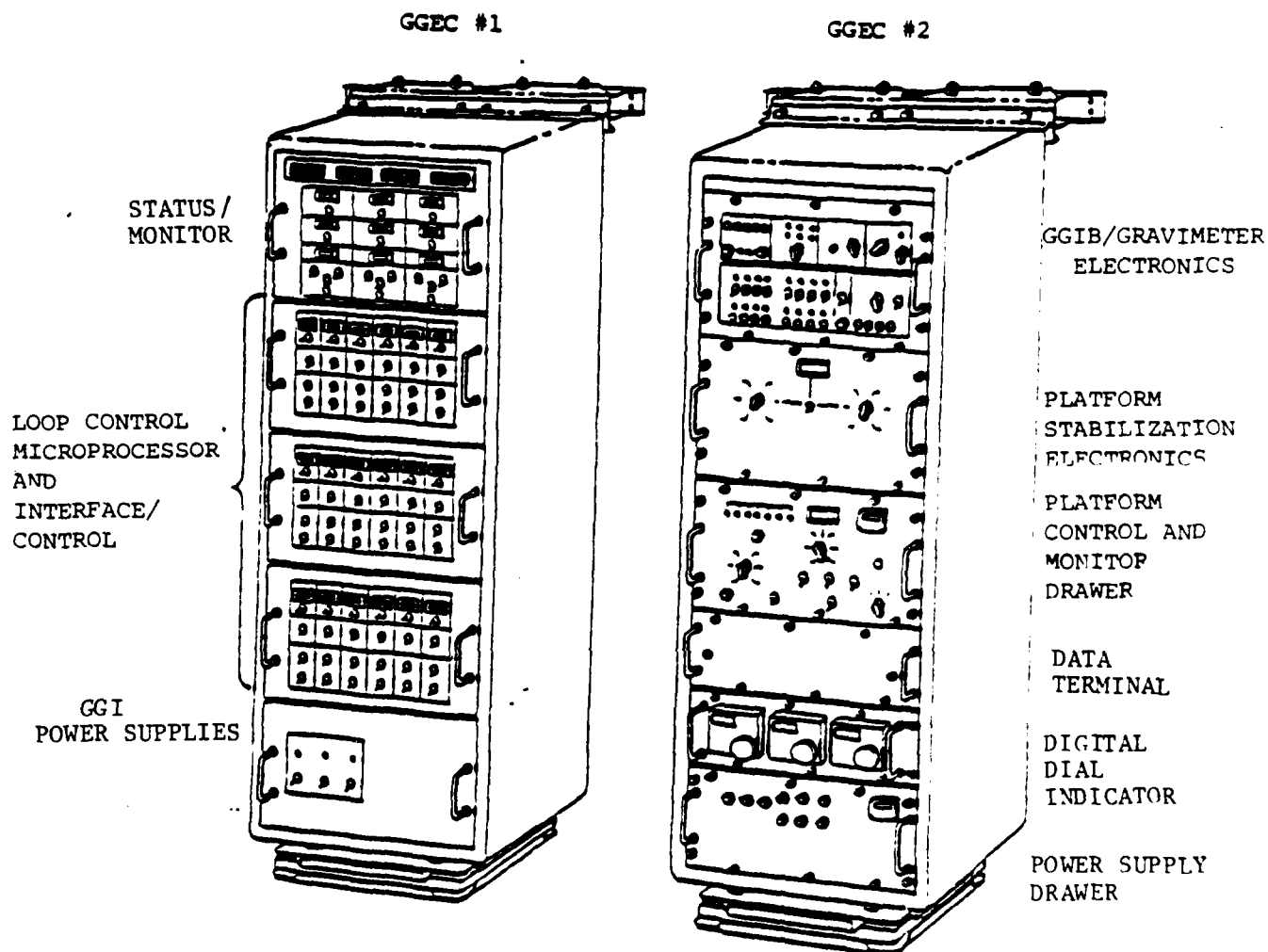


FIGURE 7-10. IGMS EQUIPMENT CABINETS

#### 7.8.1 GGEC #1

This rack contains the Status and Monitor Drawer; Three Loop Control Microprocessor and Interface Control Drawers and the GGI Power Supply drawer.

#### 7.8.2 GGEC #2

This rack contains the Gravity Gradiometer Instrument Buffer GGIB drawer, the Platform Stabilization Electronics drawer, the Platform Control and Monitor drawer, LCMP Data Terminal, Platform Control Synchros and the Power Supply drawer for the above electronics. A modification to the GSS ADM required for the IGMS is the addition of the Gravity Data Buffer electronics to process the Gravimeter data. This comparatively simple addition will be packaged in the GGIB drawer and consists of a frequency-to-digital converter (the Gravimeter accelerometer's output is a frequency proportional to the measured g level) and additional buffer electronics to assemble the digital data into the word format recognized by the Dedicated Operational Computer.

This board thus accepts the gravity data as a pulse rate and accumulates pulses for one second in a 16 bit binary counter. At the end of each one second period, the contents of the counter are transferred to a storage register and platform Data Not Valid (DNV) status, a test/operate flag bit and a code word which identifies it are added. Whenever the register contains valid data, it generates a data available flag bit which enables the buffer assembly to transfer data to the DOC. The timing of the one second intervals is provided by the GGIB.

The main features of these cabinets as described in more detail in Section 3.0 are:

- The cabinets are modified, purchased, high quality cabinets of proven design.
- The electronics are mounted in drawers along functional lines to allow drawers to be checked out in parallel without interference with the GGI's, platform and computer activities.
- The GSS can be fully operative with the electronic cabinets without the use of the Dedicated Operational Computer.
- Cooling will be by forced air.

Descriptions of the functions of all the drawers are given in more detail in Section 3.0

## 8.0 CONCLUSIONS AND RECOMMENDATIONS

### 8.1 Conclusions

1) The GSS ADM can be simply modified to meet all the requirements for a 1 milligal, 0.2 arc sec Integrated Gravity Mapping System (IGMS). The modifications are straightforward and of low risk. They consist of:

- The selections of an Inertial Navigator and Operational Computer both of which are proven, in production and available on a timely basis.
- Changing the binnacle from the overhead mounting required for shipboard installation to bottom mounting on a transportable pallet. This is a straightforward, conceptually simple design change.
- Achieving consistent reduction of the GGI higher frequency noise level to less than  $10E^2$ /rad/sec. The investigative work is in progress and error mechanisms are being identified and reduced. This task will be completed well within the schedule planned for the IGMS program.

2) The 1 milligal, 0.2 arc sec requirement can be met by the current GGI even without the improvements projected by the ongoing error reduction program with optimal mission planning. Mapping traverses and mission scenarios are readily designed such that they augment mapping accuracy. This is done by ZUPT's establishment of high accuracy tie-points and compensation algorithms which utilize closure errors to compute corrections.

3) The IGMS will be low in cost and proven in performance because the hard core development work has been essentially completed and will be proven out in the current navy test program.

4) The IGMS will be a "turn-key" system suitable for aircraft, helicopters and land vehicles. The burden of interfacing the IGMS and the mapping vehicles will be minimal. All subsystems will be mounted to pallets. Installation will consist of tying down the pallets and connecting primary power.

5) The IGMS will provide the potential of rapidly densifying significantly large areas with gravity survey points of high accuracy by transferring the known data from astrogeodetic survey points to the new sites. The 1 milligal 0.2 arc sec requirement appears easily met based on analysis.

6) All findings from the current GSS ADM test program currently underway by the US Navy will reflect improvements into the IGMS. The IGMS will benefit from well developed operational procedures and high reliability as well as improved performance from the ongoing US Navy test program whose milestones precede those of the gravity mapping program.

## 8.2 Recommendations

All recommendations are for discussion with and approval of AFGL/DMA.

1) Proceed with the modifications required to convert the GSS ADM system to the IGMS configuration. All are minimal risk conversions.

(a) Review selection criteria, cost, delivery, reliability, vendor support and possible problems associated with the selection of the AN/ASN-136 navigator and the ROLM MSE-14 computer for the IGMS application.

(b) Complete the mechanical and electrical interfacing of the selected navigator and computer with the existing GSS ADM platform and control cabinets.

(c) Complete the binnacle redesign in the areas of floor mounting, enlarged enclosure, thermal control concept and shock/vibration isolators.

(d) Proceed with software and data handling modifications.

2) Develop full scale simulation program utilizing optimal post mission data smoothing and the STAG model of the earth's gravity field. Perform parametric studies on candidate mission profiles.

3) Itemize the long lead hardware components, their costs, and evaluate impact on program schedule. Discuss findings with AFGL.

4) Initiate procurement of long lead components as directed by AFGL/DMA.

END

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